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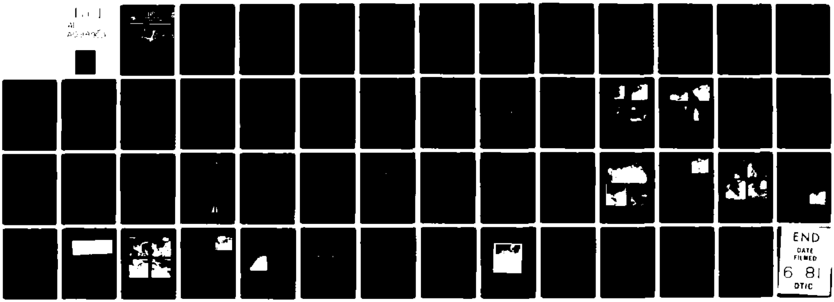

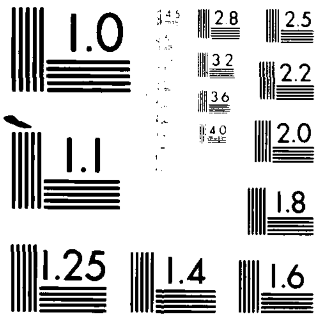

MICROCOPY RESOLUTION TEST CHART

NORDA Technical Note 87

Naval Ocean Research
and Development Activity
NSTL Station, Mississippi 39529

LEVEL II

BS 12

Variations in the Frontal Structure of the Southern Grand Banks

See 1473

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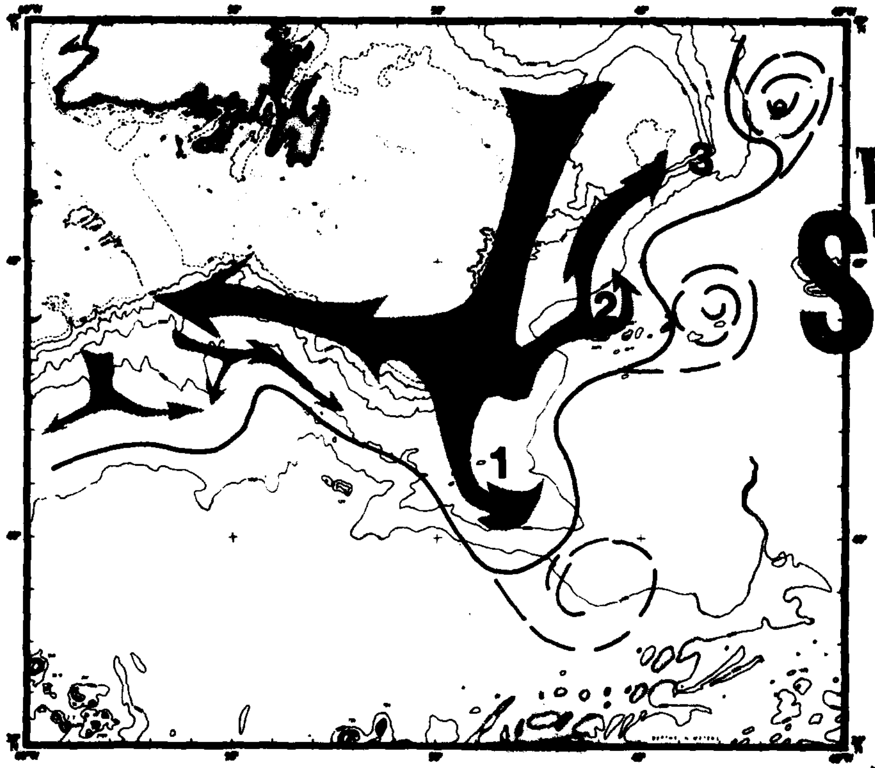

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ABSTRACT

An examination of aircraft and ship data taken as part of the Grand Banks Experiment during 1978 and 1979 and satellite data collected for the period January 1975 through October 1979, shows that the complex changing patterns of thermal gradients in the waters off the southeastern Grand Banks are different phases of large, cold-water extrusions moving away from the Labrador Front. These cold extrusions, well-delineated by their strong surface temperature gradients in the spaceborne and airborne thermal radiometry data, are found to extend as deep as 1500 meters in the shipborne salinity and temperature data. Four of the frontal extrusions are studied in detail. Three of these extrusions are found to be always in some phase of extension, with the actual speed of extension varying considerably. Moreover, the three features are found to consistently overlay specific bathymetric rises: the Newfoundland Ridge, the Newfoundland Seamounts and the Flemish Cap. The fourth cold-water extrusion, which extended south along 49°30'W in some of the data, did not appear to be topographically influenced.

ACKNOWLEDGEMENT

In a project as involved as the Grand Banks Experiment, it is difficult to acknowledge the efforts of some without feeling that numerous others equally deserving of thanks are ignored. Still, special thanks must be extended to the people of Atmospheric-Environmental Service, Toronto, and Shoe Cove Station, Newfoundland, for the excellent support they gave in providing satellite imagery; to our friends at C-CORE, Memorial University, for their excellent logistic support; to the crews of VXN-8 for flying a number of extremely difficult and sometimes dangerous missions; and for my wonderful wife, Stella, who was on the LYNCH during the storm.

1. INTRODUCTION

The surveys described in this study were made as part of a US-Canadian cooperative effort called the Grand Banks Experiment. The main purpose of the Grand Banks Experiment was to determine if data from aircraft and satellite-specialized radar and microwave radiometers could detect the variations in oceanic roughness associated with the frontal structure of current boundaries. The rationale for these ideas are better described in La Violette, et al. (1980). In order to reliably define the locations of the complex frontal boundaries involved in the Grand Banks Experiment, a synoptic oceanographic study had to be made. The results of this oceanographic study are presented here in this report.

The waters southeast of the Grand Banks have long been of oceanographic interest in that the area contains the easternmost reach of the Gulf Stream. A controversy exists over what actually happens to the Gulf Stream once it encounters the bathymetric rise known as the Southeast Newfoundland Ridge. This conflict centers around the claim by Worthington (1962, 1976) that a permanent low-pressure trough exists over the ridge, blocking further eastward flow of the Stream (Figure 1). According to Worthington, the total flow of the Gulf Stream is therefore deflected southward toward the Sargasso Sea and little, if any, mixing occurs between the Gulf Stream and the North Atlantic water on the other side of the bathymetric ridge. Worthington's proof of this theory lies mostly with the difference between Gulf Stream and North Atlantic waters in oxygen richness in the thermocline and deep layers, and a slight salinity variation in mid-depth layers.

Mann (1967), on the other hand, elaborates on a theory first advanced by Islen (1936), that the Stream splits into two branches south of the Grand Banks (Figure 2). Using April/May 1963 and June/July 1964 data collected by the CCS BAFFIN, Mann shows that a branch of the Gulf Stream loops back at 38°30'N, 44°W to join the North Atlantic Current. Mann states that in the shallower regions of the Southeast Newfoundland Ridge closer to the Grand Banks, Slope Water overrides the ridge and also joins the North Atlantic Current. In effect, Mann allows that a permanent low-pressure trough may be present, but that a branch of the Gulf Stream loops around it and that Slope Water penetrates it.

In contrast to Worthington's reason for the observed oxygen difference between Gulf Stream and North Atlantic waters, Mann hypothesizes that the oxygen difference is due to fresh oxygen supplied by a permanent anti-cyclonic warm eddy located in the Newfoundland Basin northeast of the Ridge.

Much of the oceanographic data collected in the area have been taken by vessels of the International Ice Patrol, which was formed to monitor the movement of ice in the Grand Banks region. Since this ice movement is mostly controlled by regional currents, a systematic method of collecting ocean station data to obtain mean dynamic topography began in 1922. Based on these data, mean dynamic topographies (using 1000 m as a reference level) for the months of the iceberg season (April, May and June) were calculated by Soule (1964). An example of the mean topographies for May is shown in Figure 3.

Mann (1972), in a review of studies made until 1972, decried the sparsity of data available for analysis. He hoped that the problem would be resolved by the data collected during a three-ship survey that took place in April, May, and June 1972. Clarke, et al. (1980), reporting on the results of this three-ship survey, show what they considered to be conclusive proof that the Gulf Stream did indeed split into two branches, with the greater amount of Gulf Stream water turning southward and the smaller portion joining the North Atlantic waters.

The author feels that the problem in studying the dynamics of this complex region has not been insufficient data, but rather a lack of synoptic data. Certainly the International Ice Patrol data set is not a small amount. However, these data represent repeated looks at standard locations, with no account being taken that these positions in any one year may not best describe the regional dynamic structure. Compilations of these data into mean dynamic topographies, such as composed by Soule (1964), can easily hide transient variations that may not be trivial. Also, the use of 1000 m as a reference level in this region may not be the optimum depth to use. As will be shown later in this study, the dynamic features in the region were found to extend as deep as 1500 meters.

The 1972 three-ship survey has been the nearest attempt toward synoptic data collection of the region. Even this survey, because of the large area involved, was spread over a rather long period of time--April, May and June--a period in which, at least in the upper layers, an entire season had transpired. Studies on the results of the survey (Reiniger and Clarke, 1975, and Clarke, et al., 1980) are centered about the May data. Temporal and areal variations apparent when the closely spaced XBT data are examined, are masked in the data from the broader-spaced CTD stations.

Clarke, et al. (1980) realized this problem quite well and apologize for the smoothing that was necessary to display their results. In discussing the XBT data analyses, they state, "This feature was completely missed by the coarse hydrographic station spacing...The continuation of the ridge, 'i.e., the low-pressure trough over the Newfoundland Ridge,' rather than being the smooth feature suggested by the station data, contains isolated domes of depth <500 meters more suggestive of a line of eddies than a continuous ridge...clearly the current field in the general area of the ridge must have been quite complex with closed eddies and several northward and southward flows."

Recently developed computer techniques now enable oceanographers to study the synoptic details of an area as complex as the southeast Grand Banks by using a blend of ship, aircraft, and satellite data (Holyer, et al., 1980). La Violette (1974) and La Violette, et al. (1975) showed that data from satellites can be used in the field to operationally control the survey of a complex area, and for the post-survey analysis, can be used in combination with conventionally collected data. In such a survey, remotely sensed data from satellites and aircraft would be used to provide broad, synoptic area coverage, and in situ data from ships would be used to intensely examine small critical regions within the larger study area.

The present study was made in this fashion. Data from ships, aircraft, and satellites were collected in the waters southeast of the Grand Banks in two survey phases: June 1978 (Baseline) and in May, July, and August 1979 (New Look). The oceanographic data collection made during Baseline was designed to do what the name implied -- collect broad, synoptic information in order to establish a data base of the area. The data collected during the New Look surveys were oriented to examine selected smaller scale phenomena noted during the Baseline data analysis.

The general area surveyed by the ship and aircraft is shown in the boxed sections of Figures 1 through 4. The bathymetric chart of Figure 4 is especially important, as the ocean features discussed later in this study show a strong correlation to the regional bathymetry.

2. THE SATELLITE DATA

The data collected by ship and aircraft during Baseline and New Look were handled in the conventional manner for these types of survey platforms. Since the

collection of data by satellites may be unfamiliar to the reader, and their use in this study is somewhat novel, remarks describing their collection and application may be useful.

The satellites used are NOAA-4 and 5 and TIROS-N. The sensors used are the VHRR (Very High Resolution Radiometer) infrared channel of NOAA-4 and 5 and the AVHRR (Advanced Very High Resolution Radiometer) infrared channel of TIROS-N. These channels operate within the spectral window of 10.5 to 12.5 microns and present pictures of the earth's emitted infrared energy with a 1.1 km resolution. A description of the NOAA satellite and the VHRR sensor can be found in Schwalb (1972), Fortuna and Hambrick (1974), and Koffler (1976). TIROS-N and the AVHRR sensor are described in Schwalb (1978) and Hussey (1979). Examples of the use of data of these type for oceanographic studies are numerous. Several papers for which the author was responsiole may serve as a guide to readers unfamiliar with the application of satellite data to oceanography: La Violette, 1974; La Violette et al., 1975; La Violette et al., 1980.

NOAA-4 and 5 data were used for the pre-survey satellite imagery examination and the Baseline data analysis. TIROS-N data were used in the analysis of New Look data. NOAA-4 and 5 data are somewhat limited in that it is quantitatively difficult to compare a single infrared image from these satellite's data to other imagery or surface data. This difficulty results because the earth scene shown in each NOAA image is distorted by the projection resulting from the large scan angle at the edge of the satellite sensor field of view and the curvature of the earth. Since the satellite precesses in its orbit around the earth, the same distortion is repeated only after a number of weeks. It is rare that two cloud-free images having oceanic features of interest have the same distortion. Because of problems which include the attitude of the spacecraft and the comparatively poor timing of the spacecraft clocks, it is difficult to reregister the various distortions to a common projection.

TIROS-N was launched in October 1978 and its data became operationally available in time for the New Look surveys. The TIROS-N data tapes distributed by NOAA Environmental Data Information Service (EDIS) have incorporated geographic positions derived from ephemeris data. Clark and La Violette (1980), in a study of the accuracy of the geographic positioning incorporated into the data, have measured a mean positioning error in the data of 3.7 km with a standard deviation of 1.7 km. With this degree of accuracy, TIROS-N data may be reliable registered into various map projections and an image-to-image quantitative comparison of TIROS-N satellite data is possible. The TIROS-N imagery in the New Look portion of this study have been registered into mercator projections.

The satellite data for this study were received by stations at Wallops Island, Virginia; Toronto, Ontario; and Shoe Cove, Newfoundland. Whenever possible the imagery have been enhanced to show ocean thermal features. The enhancement of the NOAA-5 imagery was done by the Canadian Atmospheric Environmental Service in Toronto, Canada. The registered TIROS-N imagery (as well as the computer-composed graphics used in the study) were made by the NORDA-IDSIPS interactive computer (Holyer, et al., 1980, and Pressman and Holyer, 1978).

3. THE PRE-SURVEY SATELLITE DATA

In preparation for the Baseline and New Look surveys and as an aid to the post-survey analyses, NOAA-4 and 5 satellite imagery for the period of January 1975 through May 1978 were examined. This pre-survey examination was later entended through the Grand Banks Experiment surveys period and terminated in October 1979.

Thus, for this study, satellite imagery for five years -- January 1975 through October 1979 -- were examined.

Quantitative comparison of the pre-survey NOAA-4 and 5 imagery is difficult because of the distortion problems discussed in the previous section. The analysis, therefore, was done qualitatively by transferring by hand the main gradient features seen in the imagery onto a common grid. Although this method is crude, certain persistent features become apparent. These features appear as extrusions of cold water which are continuously being extended away from the Labrador Front into the warmer Atlantic waters. A composite drawing resulting from the examination of the 1978 imagery is shown in Figure 5.

Clouds are always a problem in utilizing infrared satellite data for oceanographic analysis. Needless to say, in an area of rapidly moving atmospheric fronts such as the Grand Banks, the weather is often cloudy and long periods of a wook or more can pass without seeing the ocean frontal features in the satellite imagery. Thus, monitoring the extrusions for any extended period using NOAA-4 and 5 data is seldom possible. All that could be positively ascertained from the pre-survey study is that large amounts of cold water were being extruded from common nodal points along the front. Moreover, these nodal points are found to overlay three bathymetric features: The Southeast Newfoundland Ridge, the Newfoundland Seamounts and the Flemish Cap.

There appears to be no periodicity to the growth and decline of the extrusions. In addition, the speed of movement varies considerable -- at times a feature will show little movement and then begin to move rapidly. Because of the regional cloud cover and the problems mentioned with NOAA-4 and 5 data, it is difficult to make quantative measurements of the movements. Since this was a pre-survey study, more intensive examination was not instigated.

The examination of the cloud-free satellite imagery indicates that in the area of the Southwest Newfoundland Ridge, extrusions of cold water over the Ridge are normal occurrences (Figures 5 and Table A). For example in Figure 5, May 6, 1976 may be considered the nonextended case whereas the other images may be considered different phases of extension.

Exceptions occur in the months of July and August when seasonally high atmospheric moisture and comparatively low ocean thermal gradients make the definition of surface features difficult. (In the satellite data for part of the New Look survey phase -- July and August 1979, on only one day was the atmospheric moisture content low enough for the Newfoundland Ridge feature to be seen. This day's imagery and survey associated with it will be detailed in Section 5.)

The Newfoundland Seamounts' frontal feature also shows cyclic extrusions in all of the cloud-free imagery. These extrusions are seen in the imagery to develop into well-defined gyres with long filaments of cold water tying the feature to the Labrador Front. In none of the imagery is the gyre found further east than 43°W. An example of this is especially well displayed in the May 1979 survey which will be detailed in Section 5.

The Flemish Cap region was considerably more cloud covered than the area south of 45°N. However, the comparatively few cloud-free imagery of the region that are available, show the feature to be persistent and similar to those found further to the south (Figure 5 and Table A). Like the feature over the Newfoundland Seamounts, the Flemish Cap extrusion usually developed into a well-defined gyre. No aircraft or ship survey was made in this region during either Baseline or New Look since it

lay north of the Grand Banks Experiment area (the region was cloud covered during Baseline). Because of the strong similarity the Flemish Cap has to the extrusions within the Grand Banks Experiment survey area, it has been included in this study.

It is interesting to note that very few completely separate eddies (such as shown in the infrared image of 20 May 1975 -- Figure 5) were found in the several years of satellite imagery. The average was three each year. Cloud conditions prevented monitoring either the movement or longevity of those eddies that were found. Normally, the eddies seemed to last slightly less than one month, although in 1977, one eddy lasted for three months. Thin filaments of cold-water tying the developing eddies or gyres to the Labrador Front are normally present. It may be that such ties are needed to maintain the viability of the feature. No eddy whose origin was the cold-water extrusion over the Southeast Newfoundland Ridge was found south of 38°N, nor east of 42°W. Because of the clouds, however, it cannot be definitely said that none went beyond this latitude and longitude.

4. BASELINE DATA, JUNE 1978

Baseline took place during the period of 14 through 27 June 1978. The survey platforms and the sensor instrumentation relevant to this study are listed in Table B. Altogether, the Navy P-3 aircraft made seven survey flights starting on 14 June and ending on 27 June. The USNS LYNCH entered the area on 14 June and departed on 25 June. The USCGC EVERGREEN entered the area on 19 June and left on 21 June. A satellite drifter buoy was released north of the study area by the EVERGREEN on 13 April.

Analyses of the data collected by the aircraft and ship show that the cold features delineated in the simultaneously collected satellite infrared imagery were the surface manifestations of large ocean fronts which extended more than 1500 m below the surface. Figures 6 through 14 give correlative evidence of this. In addition, analyses show that these frontal structures moved during the survey period. The most interesting movement occurred over the Southeast Newfoundland Ridge, and it was there that the ship and aircraft data collection were concentrated.

By the end of the two-week survey, a major frontal structure with a large eddy-like feature at its terminus had been extruded more than 140 km from the southeastern corner of the Labrador Front. The initial position of this movement can be seen in the 12 June satellite infrared imagery in Figure 6 and the aircraft precision radiation thermometer (PRT) data in Figure 7. The movement culminates in the frontal position shown by the 25 June satellite image and the 27 June aircraft PRT analysis. The step-by-step extrusion away from the initial position is shown in the overlay of major thermal gradients derived from PRT data in Figure 8. The end of the Baseline survey occurred on 27 June. Unfortunately, clouds and the onset of seasonal high humidity obscured satellite views of the sea surface temperature gradients for the next two months. Whether the protuberance at the end of the extruding front broke off and became an independent eddy is not known.

This extrusive movement is especially interesting when the vertical thickness of the frontal cold feature is considered. Cross Sections constructed from ship 750 m expendable bathythermographs (XBTs) show that the feature extended at least to the bottom of the XBT traces (Figure 11). STD casts taken by the ship show that the salinity and temperature within the feature differed from the salinity and temperature outside the feature as deep as 1500 m (Figure 12).

Examination of the data taken by 350 m XBTs dropped by aircraft ahead of the extruding cold front shows no evidence of any previous cold structure which may have

sunk below the surface. This can be seen in the XBT analysis for 300 m temperatures in Figure 8 and in the sample aircraft XBTs in Figure 13. Unfortunately, the LYNCH did not go into the area ahead of the extruded front, and information deeper than 350 m, such as from 750 m XBT and STD data, are not available. The XBT analyses for 23 June in Figure 14 show that the moving front retained its thickness at least down to the bottom of the aircraft XBT traces.

Two temperature minimums are found in all of the XBTs dropped inside the cold frontal feature. The shallowest of these forms a narrow ribbon of cold water whose core is <3°C. This cold ribbon seems to be of Labrador Water origin and a connection between the cold water extrusion and the cold Labrador Water to the northwest can be traced using the Baseline XBT data. Examples of this connection for the 17/18 and 23 June flights are shown in Figure 15. It is interesting to note that at a depth of between 50 and 100 m, the narrow ribbon of cold water penetrates the warm water ridge separating the two pools of <6°C water in Figure 9. Two shallow minimums--one on the southwestern and the other on the northeastern side of the cold feature are shown in the cross-section analysis of ship XBT data in Figure 11. However, only one shallow minimum--on the southwestern side--is shown in the same area in the 17/18 June analyses in Figure 15. This discrepancy may be a result of the spacing of the aircraft XBT drops rather than the horizontal movement of the cold ribbon between 14 and 17 June.

The salinity of the cold water extrusion was low, reflecting its Labrador water origin. A surface salinity chart is shown in Figure 16 for the period 14 through 18 June 1978. The cold water feature shows only slight movement during four of this five-day period according to the analysis of the aircraft PRT data of 14/15 and 17/18 June (Figures 7 and 8). (An examination of the satellite data indicates that the extrusive movement actually started on 18 June. This movement is not seen in the analysis of PRT data for 17/18 June, since the eastern portion of the area was flown on 17 June and the western portion was flown on 18 June.) The salinity analysis may thus be considered reasonably accurate for the four-day period.

In order to obtain as near-synoptic sampling as possible, the USNS LYNCH made a non-stop run through the study area from 14 through 18 June, collecting surface water samples, meteorological data, and dropping XBTs in passage. Therefore, no STDs were taken during this time, and no data for subsurface salinity analysis for the period are available. The salinity data from subsequent STD casts cannot be made into areal charts, both because of the comparative sparsity of the STD stations and because of the obvious movement of the cold water which took place on and after 18 June 1978.

Two other extrusive features were examined during Baseline -- one at 49°30'W and the other overlying the Newfoundland Sea Mounts (the Flemish Cap was cloud covered during the Baseline survey).

The cold, southward extensions along 49°30'W is shown by the Baseline data to have become slightly more developed as the survey continued but with little other change. The east-west thinness of the feature and the comparatively wide spacing of the ship and airborne XBTs make intensive examination of the feature difficult. The subsurface cold ribbon of <3°C water may have extended farther southward inside the feature than is shown by the analyses of 17/18 June data in Figure 15, but was missed by the XBT placement (the possibility of this extension is indicated by the 0°C temperature of the core of the first minimum at 49°30'W, 41°15'N).

A satellite drifter buoy was released into the Labrador Current at 48°31'N, 48°59'W by the USCGC EVERGREEN on 13 April (Richardson, 1980). In Figure 17, (a)

and (c) shows its southward movement within the current. The movement of the drifter buoy may be compared to the position of the thin, cold core of the Labrador Current visible in the 12 June satellite image (Figure 6). The close match of the current position in the 12 June satellite image and the two-month drifter track gives an indication of the persistence of the location of the current.

At 51°30'W, the buoy turned eastward and on 30 May became caught in the flow of the southward extension at 49°30'W. The data show that the buoy remained within the southern limit of the extension until the end of tracking on 22 June. The examination of the several years of collected satellite imagery indicates that, although the cold feature at 49°30'W was found occasionally, it is not a persistent in the imagery nor does the feature seem to have the cyclic nature of the New foundland Ridge feature. A more intensive study is needed using the registered data of TIROS-N*.

The cold frontal feature over the Newfoundland Seamounts also showed strong extension during Baseline. Although neither the aircraft nor the ships entered this region (except to show the beginning of northeast arcing of the thermal gradients, north of 43°N in the 17-18 June aircraft data analysis), the satellite imagery did show feature development from 12 to 25 June that was similar to the cold extrusion over the Southeast Newfoundland Ridge (Figure 6). A satellite-drifter buoy, dropped by the USNS LYNCH on the eastern side of the Newfoundland Ridge feature, followed the thermal gradients northeastward at an average speed of slightly over 100 cm/sec (Figure 17). North of 43°N, the drifter began to follow a course which outlines the cold water feature over the Seamounts shown in the northern portion of the 25 June satellite image.

5. NEW LOOK DATA - MAY, JULY AND AUGUST 1979

The second phase of the Grand Banks Experiment was made in 1979. This phase was accomplished in two steps: the first in the period 9 through 19 May; the second in the period 28 July through 14 August. The instruments used and their platforms are listed in Table B.

During the May survey, only aircraft and satellites were used as data collection platforms. Two ships which were to have participated in the May survey experienced severe weather and engine breakdown and were forced to withdraw. Despite this loss, the May aircraft and satellite data furnished excellent complementary information to that provided by the Baseline data. The satellite data covered the entire area, while the aircraft measurements concentrated on details of the frontal features over the Southeast Newfoundland Ridge and the Newfoundland Seamounts (again, no flights were made over the Flemish Cap).

The TIROS-N satellite imagery for 15 May, shown in Figure 18, is a good example of the thermal gradients present over the Ridge and Seamounts during the May survey. As can be seen in this figure (and discussed in Section 2), TIROS-N data -- unlike NOAA-4 and 5 data -- are capable of accurate registration. Thus, the data from this

*It should be remarked that the TITANIC sunk after being breeched by an iceberg near the point where the cold feature leaves the Labrador Front (41°6'N - 50°44'W). It is possible that the iceberg was carried southward by an earlier, and even colder, extrusion of the Labrador Current along the line 49°30'W.

satellite can be rigorously compared to the aircraft survey data. According to the satellite imagery and a special reconnaissance flight on 9 May, no cold-water feature is found similar to the June 1978 extrusion along the line 40°30'W. In addition, data from 350 m XBTs dropped during the 9 May flight show no evidence of a remanent cold-water structure lying below the surface. Analyses of both the surface and the subsurface structure of the water over the Southeast Newfoundland Ridge based on 9 and 10 May aircraft data are shown in Figure 19. No narrow ribbon of <3°C water is seen.

The storm which plagued the ships created cloud conditions that covered the area extensively during the May survey. Despite these conditions, those satellite imagery clear enough to display ocean thermal gradients show that the frontal structure over the Southeast Newfoundland Ridge did not move appreciably during May. In addition, a comparison of the aircraft PRT analysis for 9 and 10 May with the ocean thermal features shown in the 15 May satellite image shows very little southeast extension of the structure occurred during the five-day interval (Figure 19). However, some circulatory movement is visible in comparing the registered imagery for 13, 14, 15 and 16 May shown in Figure 20. The Ridge feature in the 16 May image is slightly wider and shorter than in the imagery for the other three days. This change gives the appearance that a more circular structure was forming (the termination of the survey and cloud conditions prevented monitoring the front beyond this date).

The arrows in Figure 20 follow the movement of smaller scale details within the Ridge feature during the four-day period. Along the western front of the feature, the arrows track what appears to be frontal waves moving southeasterly at a speed of 65 cm/sec. A cross section of the cold water feature made from aircraft XBT data taken on 16 May show the thermal front to be extremely steep with almost no thermocline at the northernmost of the three arrows (Figure 21). Similar steep structure was found across the front 50 km further southeast on 17 May in the analysis of aircraft XBT data. The steepness of the vertical thermal structure of the frontal edge, as well as the regularity of the waves, seems to indicate two possibilities, one, that the frontal wave motion was causing lateral northeast/southwest displacement of the cold frontal edge. Two, that cold water was being transported to the southeast along the front in geostrophic balance with the pressure field across the front.

Examination of the movement seen in the imagery of Figure 20 in the northernmost portion of the Ridge feature seems to indicate that here, at least, some transport of water was taking place. Several large filaments of cold water had a surprising ability to maintain their identifying shapes, and are shown to move southwestward. Unfortunately, no airborne XBTs were dropped in these features and their vertical structure is not known.

In order to obtain some feel for the surface currents across the Southeast Newfoundland Ridge feature, 38 sonobuoys were air dropped to form a right angle cut across the entire feature fronts on 16 and 17 May (Figure 22). The drops were made along the same track for both days with 9 km spacing and their receivers set at 60 m. At the end of approximately two hours and twenty minutes on 16 May and three hours on 17 May, the lines were reflown and the buoys tracked using the aircraft Inertial Navigation System (INS) to accurately position their new locations. Because the path of the aircraft during the dropping of the buoys and their tracking was in the same direction, the amount of time that each buoy drifted before being relocated was fairly uniform. On 16 May, the total variation in drift time for the 15 buoys was less than five seconds; on 17 May the variation was eleven minutes and five seconds.

The aircraft drift during these flights (as determined by the INS) was used to compute the wind speed at the altitude of the aircraft (300 m) This shows that on 16 May the winds were from the east at 5 m/sec. On 17 May, the winds increased, being 8.7 m/sec out of the east southeast over the eastern front region and gradually building to 14.4 m/sec and shifting to the north-northeast over the western front. No wind variations are noticeable in the data for the period when the aircraft flew over either of the ocean fronts.

The analysis of the sonobuoy data show the actual current along the western front was moving faster than the frontal waves shown in Figure 20. In addition, the data analysis indicates that the current along the western edge was parallel to the front. On the other hand, the movement within the cold water and in the area of the eastern front indicates a definite trend northward.

In addition to the sonobuoys, six dye markers were dropped in a straight line between sonobuoy positions 3 and 5 on 16 May (Figures 22 and 23). The third dye marker and fourth sonobuoy were dropped simultaneously where the PRT marked the western front. The positions shown in the photo mosaic are their drift after one hour and ten minutes. Although not discernable in the nadir-oriented photographs, the front, laying almost exactly on dye marker 3 and at right angles to the plane's flight, was plainly visible from the aircraft. The front was also visible as a sharp change in sea clutter on the aircraft meteorological search radar.

On 19 May, an area survey was made of the cold water gyre lying over the Newfoundland Seamounts. The feature had been visible in the satellite infrared imagery for several days, but became hidden under clouds two days prior to the flight. The gyre, as seen in best detail in the satellite image for 15 May in Figure 24, extends over an area 200 km on its east-west axis and 100 km on its north north-south axis. Two feeder arms of cold Labrador water appear to be nurturing the feature; that these were active is evidenced by the arrows tracking a frontal wave of cold water that is being transported into the center of the gyre in Figure 24. This frontal waves moved at an average speed of approximately 35 cm/sec until 15 May. Between 15 and 16 May, as the wave entered the center of the gyre, the speed increased to 50 cm/sec.

The 19 May aircraft XBT data analysis in Figure 25 shows surface structure similar to the gyre appearing in the previous day's satellite imagery. (Atmospheric moisture in the form of low clouds and fog, prevented the collection of good quality PRT data, and data from the aircraft XBTs were used to compose the surface charts shown in Figure 25.) These areal displays show that the complexities of the surface extended beyond the bottom of the XBT traces with strong movement at all levels. Double minimums with shallow minimums of $<3^{\circ}C$ are seen scattered at various levels in the data. These low temperatures seem to be indicative of parcels of very cold water (as opposed to continuous ribbon-like bands) being transported into the center of the gyre.

In general, the stronger surface gradients and more complex vertical structure of the Newfoundland Seamount frontal feature displayed in the satellite imagery and aircraft data analysis show this frontal feature to be at a far more dynamic stage of development than the Ridge feature to the south.

The last part of the New Look survey took place in July and August 1979. This portion of New Look was designed to show that the cold water feature over the Newfoundland Ridge was present during a period when seasonally high humidity often obscured the region from the view of infrared satellite sensors.

The survey consisted of the USNS LYNCH making 750 m XBT drops while running a diagonal cut across the Southeast Newfoundland Ridge and partially over the Newfoundland Seamounts (Figure 26). Two runs were made two weeks apart. The first run was made 28 through 31 July and the second 11 through 14 August (Figure 27). Aircraft PRT and XBT data collected along the same tracklines at the same time, backed up the ship data. Because of the similarity of the two data sets, only the analysis of the ship data are presented here. Satellite infrared imagery of the area are extremely poor due to atmospheric moisture contamination. The only usable image for the period occurred on 28 July, and is shown in Figure 25 with the ship track superimposed. Because of the poor satellite imagery, the ship and aircraft tracks had to be planned without real-time information. As the ship track in Figure 26 shows this lack of information almost resulted in the cold feature being missed.

The 750 m XBT cross-sections and the satellite imagery show that the Southeastern Newfoundland Ridge and the Newfoundland Seamounts features were definitely present during the summer months. The Southeast Newfoundland Ridge feature is comparatively warm, as would be expected for the time of year, and seems to be in its most withdrawn northwesterly position. The two cross sections show that no significant change had occurred in the two weeks between the two surveys Both cross sections indicate the Newfoundland Seamounts feature, was fully extended eastward. Two 750 m XBTs dropped in the Seamount feature (not included in the two cross-sections) show a double minimum, with the first minimum containing water of $<3^{\circ}C$ at the core.

The infrared image also shows a cold feature partially hidden by clouds southwest of the Ridge feature. Since no other satellite image is available for the period that shows this feature, nothing can be inferred as to its relation to the other features being studied. Some indication of the subsurface structure of this secondary feature may be seen in the southern portion of the two cross-sections.

6. DISCUSSION

One interesting aspect of the cold water extrusion over the Southeast Newfoundland Ridge is that it lies in the region where Worthington places his "permanent low-pressure trough" and, indeed, a low-pressure trough is seen in the vertical cross-sections of a number of past surveys (Worthington, 1962; Mann, 1967; Reiniger and Clarke, 1975; and Clarke, et al., 1980) During Baseline, the XBTs along Line C in Figure 11 were deliberately dropped along a track close to where a line of XBTs were dropped from R/V HUDSON on 18 May 1972 The cross sectional analysis of these HUDSON XBTs (Reininger and Clarke, 1975 -- Figure 28) compares favorably with the Line C analyses.

These analyses, as well as other analyses of XBT data showing similar structures over the Newfoundland Ridge, give an initial impression that a low-pressure trough may indeed be a permanent feature. However, one wonders what the vertical structure would have looked like had the XBTs along Line C been dropped on 12 June 1978 when the feature was slightly more northwest. Would any evidence of a low-pressure trough have been present? It must be remembered that the Baseline aircraft XBT data show no trace of any previous structure in the upper 350 m of the water column ahead of the advancing cold water extrusion. In the New Look surveys of May and July/August 1979, XBTs dropped along the same track as Line C would not have revealed a low-pressure trough. In fact, in the July/August survey, XBTs along Line B of Figure 11 would not have shown a cold feature.

If instead of a "permanent low-pressure trough", an intermittent one is considered, one that is constantly expanding and collapsing, then the seeming

inconsistancies of the data discussed above would be resolved. The analyses of the five years of satellite data and those of the Grand Banks Experiment surveys definitely show that an extrusive cold-water feature, intermittantly extending from the Labrador Front, is the structure normally formed over the Southeast Newfoundland Ridge.

The satellite and aircraft data show that until 18 June, the Ridge feature had moved at a very slow pace southeastward. However, from 18 June until the end of the survey, the movement was quite rapid (140 km in 7 days). Reininger and Clarke (1975) saw a similar southeasterly movement of cold water in their analysis of date taken by the R/V HUDSON and R/V CHAIN. In these data, the temperature field at 50 m shows that a trough of water of less than 10.C had extended itself from a position slightly north of 40°N southeasterly to almost 38°N (Figure 29).

On the other hand, the Ridge feature in the analyses of the New Look surveys of May and July/August 1979 shows very little extrusive movement. The five years of satellite imagery shows similar instances of intermittent movement. These results indicate that the speed at which the front is extruded varies considerably, sometimes moving in spurts, while at other times moving extremely slowly. The reader is reminded that regional cloud cover combined with the difficulty to accurately monitor the distorted NOAA-4 and 5 data make quantitative accounting of the Ridge movement in the pre-survey imagery difficult.

The cold, narrow ribbons of Labrador water found at 50 m in the Ridge and Seamounts features are an indication of the intense dynamic activity taking place within the extruding structures. Narrow layers of <3°C water at this level found during the Grand Bank Experiment surveys may not be unusual, as a similar temperature minimum was found at 50 m in the same area in the May 1972, R/V CHAIN data (Reiniger and Clarke, 1975 — Figure 29). The examination of the satellite imagery also shows that the breaking off of the extrusions into completely separate eddies seldom occurs. As mentioned in Section 3, the average occurrence of completely separate eddies during the five years was three each year. Normally, the imagery displayed cold-water filaments that tied the extended features with the Labrador Front. It would seem by the constant presence of these cold-water ties, that they are an indication of constant influx of cold water into the extrusion. Their absence, when an eddy is formed, may be an indication of the dynamic decay of the feature.

The extrusions presented a great deal of day-to-day internal and frontal movement in the satellite imagery. With the accurate geographic positioning possible with the TIROS-N data, it is now possible to measure the surface manifestations of these thermal movements. For example, frontal waves were seen in both the Southeast Newfoundland Ridge and the Newfoundland Seamount features. Comparison of their displacement over four consecutive days showed wave speeds of 65 cm/sec for the Ridge feature and between 35 and 50 cm/sec for the Seamount feature. In comparison, the currents associated with the fronts, according to satellite drifter buoys and sonobuoy drifts (Figures 17 and 22), were found to be moving faster than the edge waves.

The photographic mosaic of the dyes dropped on 16 May (Figure 23) may be a key to understanding some of the complex features of the front. The mosaic shows a small drift of the dyes on the cold side of the front as compared to the warm side. Without the mosaic to examine, an analysis of the sonobuoy data in Figure 22 would indicate a gradual change in current speed as the aircraft approached the center of the frontal structure. However, the mosaic suggests that the apparent gradual change in current velocity may be a result of the comparatively wide spacing of the

sonobuoys, and that the changes may instead be quite sharp, with zones of fairly uniform velocities lying in between the regions of sharp change. If this is true, then the intriguing point is that the interfaces of these zones are shear patterns; and it may be that these patterns are the linear features often associated with fronts that are visible in aircraft and satellite specialized radars.

Although the cold-water feature is found to lay generally over the Southeast Newfoundland Ridge, its actual position varies. The Ridge feature during the May 1979 survey of New Look was farther west than during Baseline. Clarke, et al. (1980) notice a similar location disparity in the position of the Ridge feature when comparing their data anlysis on the low-pressure trough to that of Mann (1967). Examination of the five years of NOAA-4 and 5 satellite imagery shows that the feature wandered in location between the extreme eastern position shown in Baseline and a point only slightly west of the May 1979 location.

The cold extrusions over the Newfoundland Seamounts and the Flemish Cap, on the other hand, are almost always directly over their bathymetric counterpart. The fact that cross fits of this nature are a consistent feature of the region indicates that the slope of the bottom has a strong control on the surface thermal patterns.

Voorheis, et al. (1973) postulate that the meanders of frontal waters over the southeast Grand Banks are bathymetrically controlled and show a simple vorticity analysis using the several months of the International Ice Patrol's mean dynamic topography analyses. They felt the good agreement which resulted argued for strong bathymetric control. In order to examine the fit empirically using TIROS-N registered data, the bathymetric chart of the area was superimposed on the 15 May image (Figure 30). The fit of any data of this type is very difficult to quantify, yet the gross fit of the surface radiant temperature features in the image with the bathymetry as deep as 4000 m is undeniable.

The registered enhanced TIROS-N imagery for 15 May 1979 used in Figures 18 and 20 indicate a direction of study which may help solve the controversy as to what happens to the Gulf Stream once it reaches the Newfoundland Ridge. In examinations of infrared satellite imagery of the Gulf Stream, the warm water abutting the cold water (such as indicated by the arrows in the unregistered image in Figure 18), is usually considered to be the North Wall of the Stream. Aircraft and ship surveys have confirmed this correlation to be normally true (see, for example, almost any issue of GULFSTREAM -- Cheney (1978) would be a good case in point). In the selectively enhanced 15 May image of Figure 18, a filament of warm water in the imagery is shown to loop around the Newfoundland Ridge feature and move to the north. This filament is visible in other TIROS-N imagery collected during the New Look survey. Since registerable TIROS-N imagery of the area is now available, it should be possible to monitor the warm water of the Gulf Stream's North Wall to see whether such branching of the current such as shown here is a permanent or an intermittent feature. This monitoring of course, must be coupled with occasional in situ temperature - salinity data collection by ship to insure that the warm water studied was indeed that of the Gulf Stream.

7. CONCLUSIONS

A comparison of the analysis of the ship and aircraft data collected as part of the Grand Banks Experiment surveys to simultaneously collected satellite data show that the distribution of thermal gradients in the two data sets agree. It is concluded, therefore, that in this area satellite imagery could be confidently used to monitor the movement of the frontal features during those times when ship and aircraft are not available.

The analyses of Grand Bank Experiment aircraft and ship data show that three dynamic frontal structures projected from the Labrador Front during 1978 and 1979. These are: an extension of cold water at 49°30'W and two cold extrusions, one over the Southeast Newfoundland Ridge and the other over the Newfoundland Seamounts.

A study of satellite imagery for a five-year period, which includes these surveys, shows that the cold frontal features over the Newfoundland Ridge and the Newfoundland Seamount are always present in some phase of extrusion -- whereas the feature along 49°30'W appears only occasionally. A fourth persistent cold extrusion, seen in the satellite imagery over the Flemish Cap, appears to be markedly similar to the Ridge and Seamount features.

The persistence of these cold extrusive frontal features throughout the year, their extension as deep as 1500 m, and their close alignment with bathymetric features deeper than 4000 m, indicate that they are not minor features caused by the local wind stress on the surface layer, but are related to the circulation of the entire water column. Their deployment and general configurations seem to suggest that they have a different genesis than the cold and warm water rings found upstream in the Gulf Stream.

Complex ocean features such as those examined in this study are impossible to either survey or analyze by conventional means alone. In the survey operations of the Grand Banks Experiment, information provided by examinations of the daily satellite imagery allowed the aircraft and ship tracks to be maximally positioned for the available survey time. In the analyses, the satellite data expanded the limited geographic and temporal information provided by the aircraft and ship data. Synoptic studies of the frontal features of the outer Grand Banks are now possible by utilizing combinations of satellite imagery with conventional aircraft and ship data collections that were not possible before. It is hoped that this study will be but a start in that direction.

TABLE A

Percentage of Visibility of Frontal Features in Southeastern Grand Banks

	Imagery Examined	% of Total Imagery Cloudy	Newfoundland Ridge		Newfoundland Seamounts		Flemish Cap	
			% Vis	% >Fair	% Vis	% > Fair	% Vis	% > Fair
Jan	117	63.2	36.7	14.5	19.7	9.4	12.0	7.7
Feb	84	57.1	39.3	14.3	19.0	10.7	2.4	1.2
Mar	63	52.4	46.0	23.8	31.7	36.5	19.0	11.1
Apr	58	53.4	46.6	24.1	19.0	13.8	8.6	6.9
May	68	42.1	47.1	30.9	25.0	22.1	7.4	7.4
Jun	62	21.0	62.9	27.4	48.4	24.2	21.0	9.7
Jul	84	41.7	56.0	9.5	41.7	11.9	14.3	4.8
Aug	94	34.0	59.6	11.7	36.2	11.7	17.0	6.4
Sep	104	36.5	57.7	31.7	38.5	29.8	24.0	16.3
Oct	138	29.3	41.3	23.2	26.1	12.3	11.6	7.2
Nov	82	74.2	39.0	24.4	24.4	13.6	9.8	7.3
Dec	101	58.4	24.7	9.9	12.9	6.4	8.9	5.9
Total or Mean	1060	50.2	46.6	20.5	28.6	16.9	13.0	7.6

Notes: The amount of imagery examined was determined by their availability in the NOAA/NESS imagery tiles in Washington, DC. for the time January 1975 through October 1979. The percentage of imagery cloudy designates times when no recognizable frontal feature could be seen because of cloud cover. The % visible under the Newfoundland Ridge, Newfoundland Seamounts, Flemish Cap headings refer only to the percent visible in the specific subregion. If an areas was clear (except the high humidity periods in July and August), the frontal feature in that area was always visible. The heading "% Vis" gives the percentage of times this occurred. The heading % $\geq$ Fair designates those times when a big enough portion of the frontal feature was visible to allow the detection of change in comparison to other day's imagery.

TABLE B

Platforms and Sensors Used During Baseline and New Look

Baseline (June 1978)

Platforms		Main Instrumentation Sensors
Ships:	USNS LYNCH (T-AGOR-7)	STD,[1] XBT,[2] surface temperatures, surface salinities,[4] satellite drifter buoy, and meteorological sensors
	USCGC EVERGREEN	XBT, surface temperatures, and satellite drifter buoy
Aircraft:	U.S. NAVOCEANO BIRDSEYE (P-3)	PRT,[5] AXBT,[6] IR scanner, and meteorological sensors
Satellites:	NOAA-4 and 5	IR and visible

NEW LOOK (May 1979)

Aircraft:	U.S. NAVOCEANO SEASCAN (P-3)	PRT, AXBT, and meteorological sensors
Satellite:	TIROS-N	IR and visible

NEW LOOK (July/August 1979)

Ship:	USNS LYNCH (T-AGOR-7)	CTD, XBT
Aircraft:	U.S. NAVOCEANO SEASCAN (P-3)	PRT, AXBT, and meteorlogical sensors
Satellite:	TIROS-N	IR and visible

NOTES:

Data collection and calibration methods:

1. Presurvey calibration and field rossette sample checks
2. Standard Sipicon XBTs, no field calibration
3. Bucket temperatures with calibrated thermometers
4. Autosal model 8400 salinometer
5. Barnes PRT-5 inflight bath calibration with upward-looking PRT's for sky correction
6. Pre-survey bath calibration

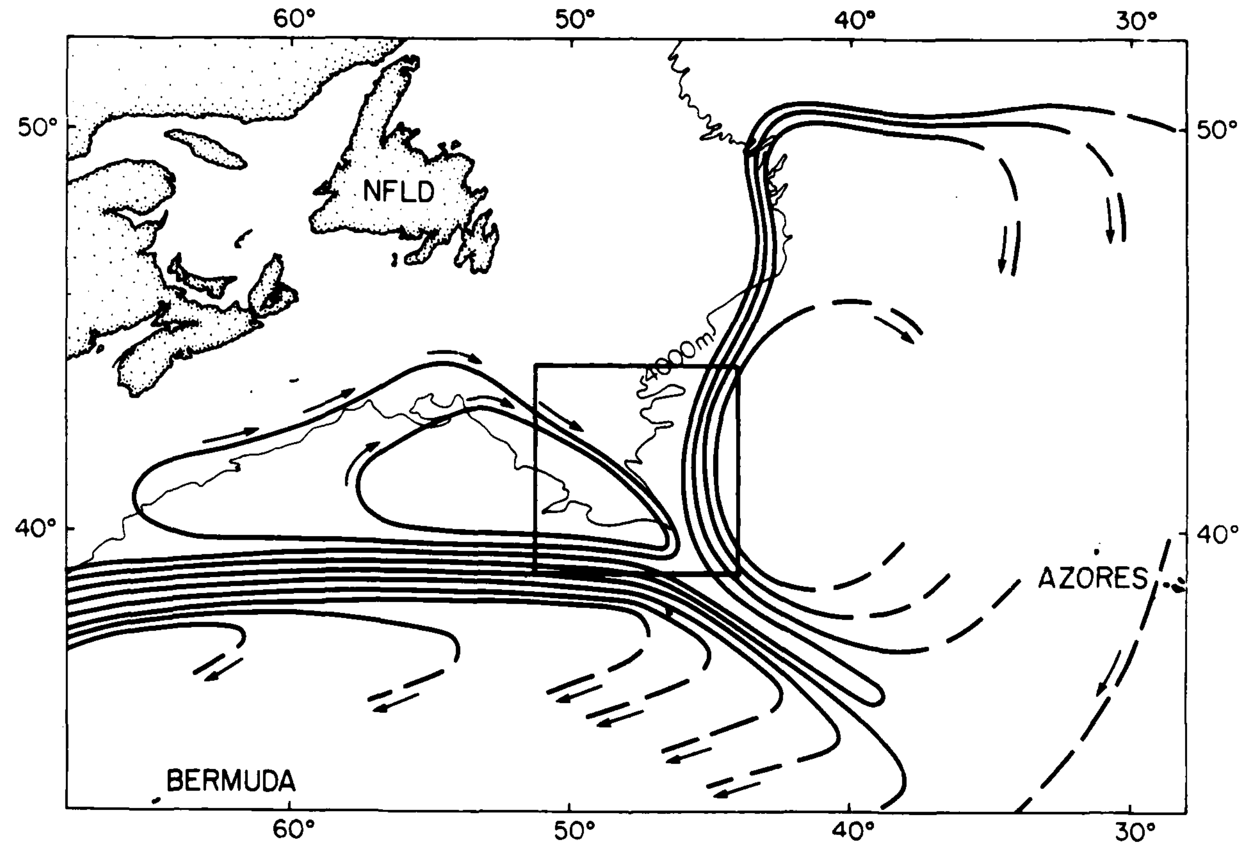


Figure 1. A chart from Worthington (1962) showing the water budget relative to 2000 m for the northeastern North Atlantic. Each streamline represents a transport of 10 x 10^6 m^3/sec. The square encloses the area of the present study.

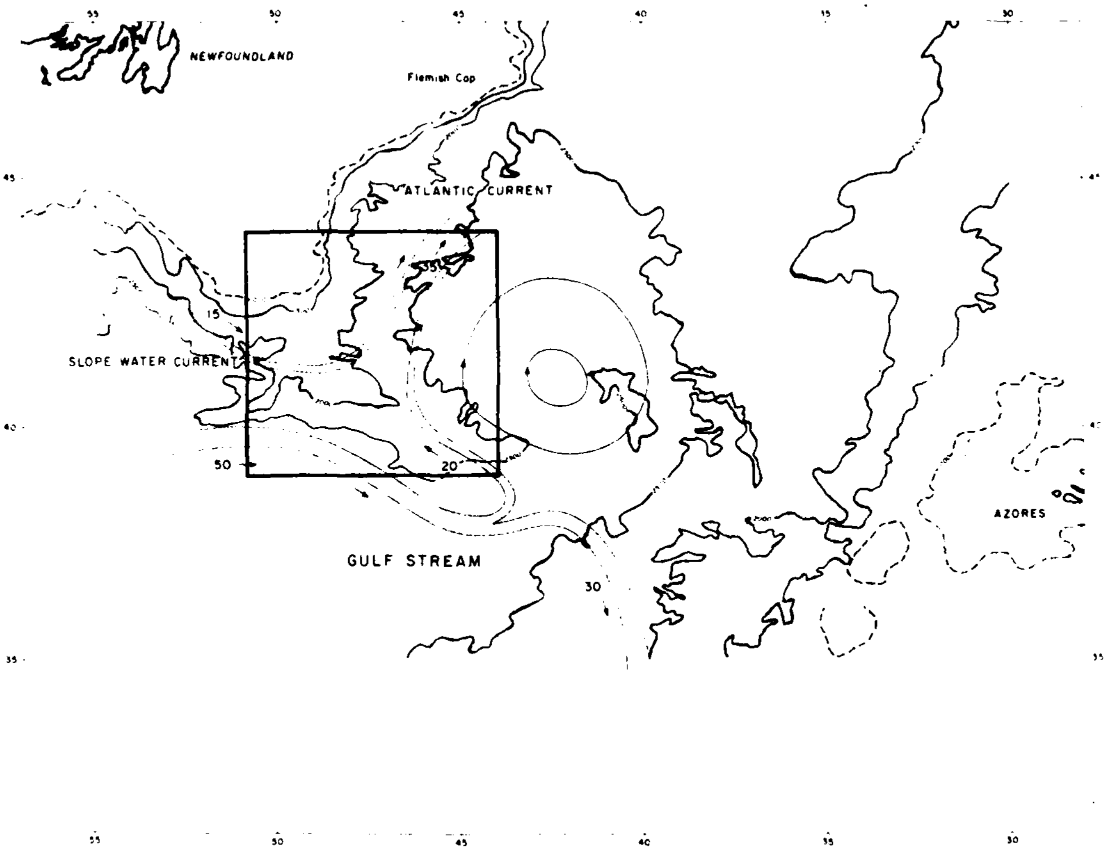


Figure 2. The current system southeast of the Grand Banks according to Mann (1967). Nominal transports are in 10^6 m^3/sec. The square encloses the area of the present study.

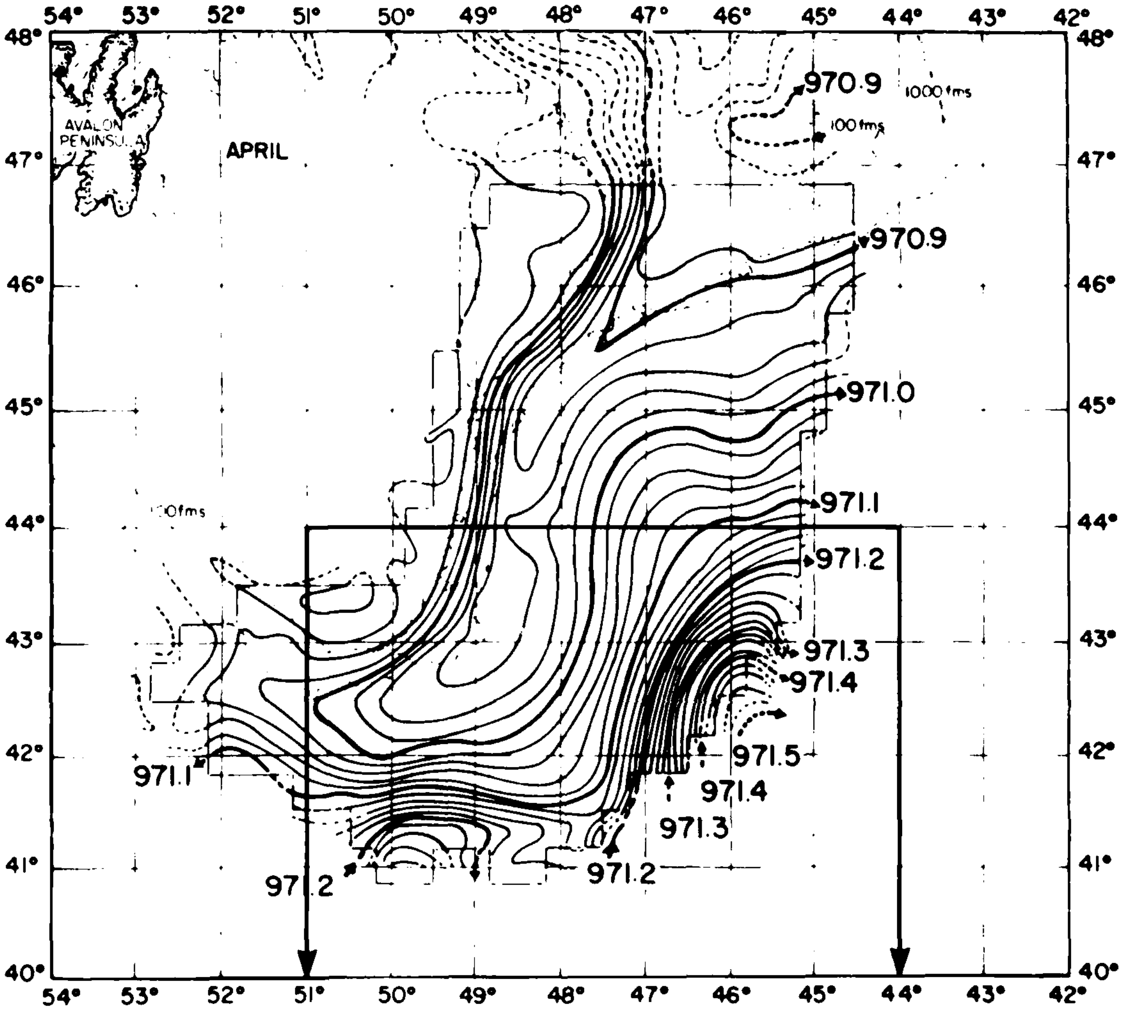


Figure 3. Mean dynamic topographies southeast of the Grand Banks for May as compiled by the International Ice Patrol after Soule (1964). The values are in dynamic meters with 1000 m as the level of no motion. The square encloses that portion of the figure discussed in the present study.

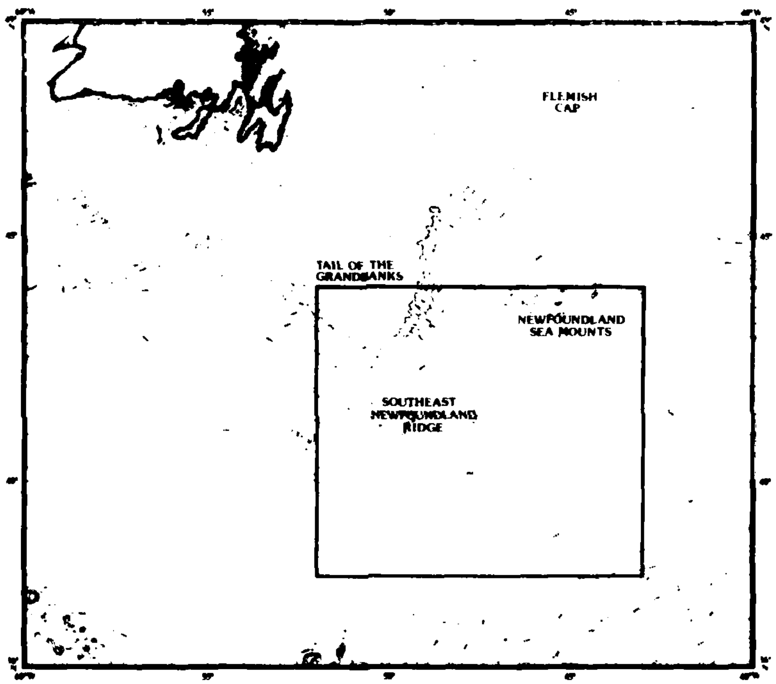


Figure 4. The bathymetry in meters of the southeast Grand Banks. The square encloses the area of the present study.

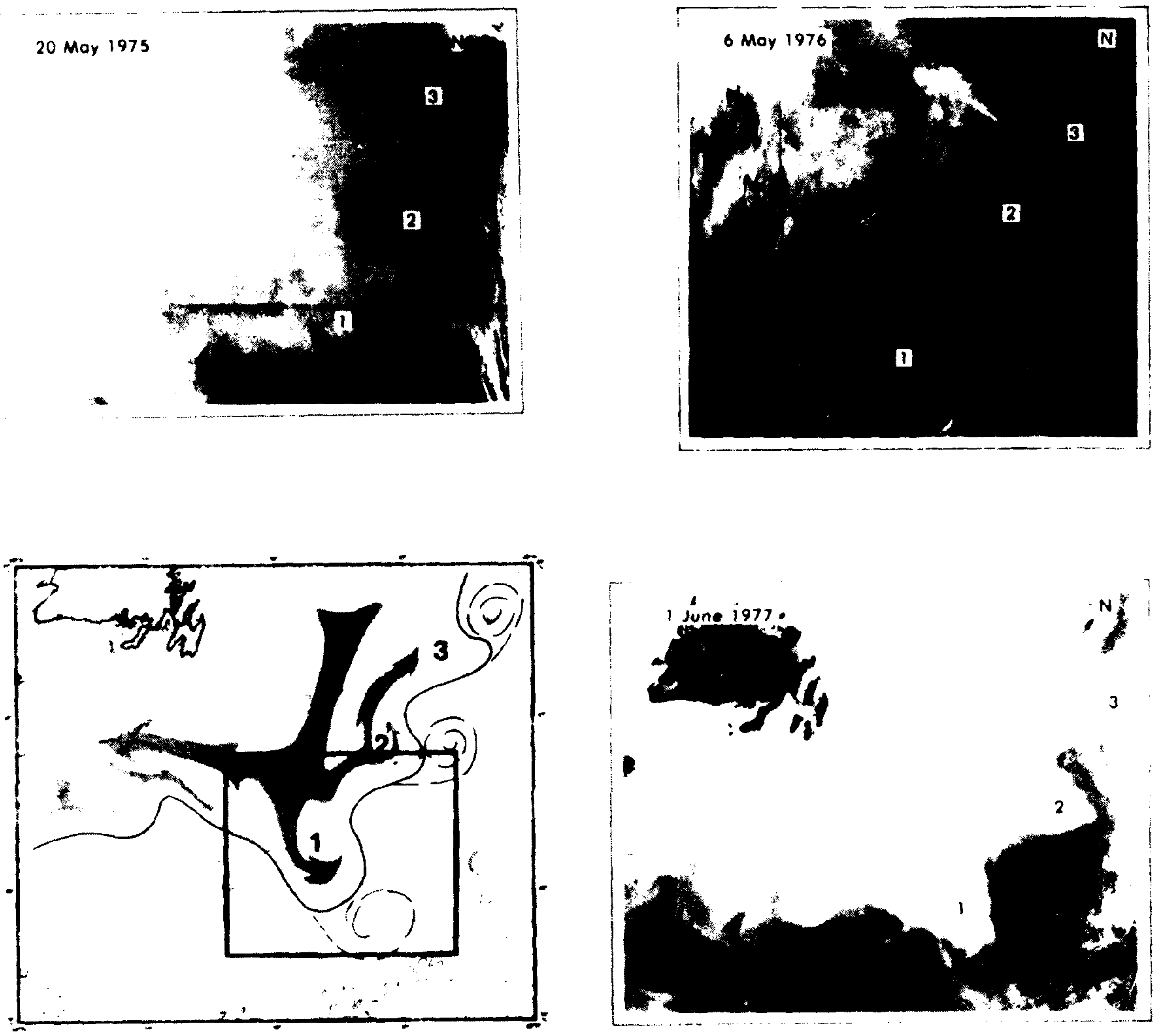


Figure 5. Satellite infrared imagery for the period January 1975 through October 1979 show that three frontal extrusions were always present in the cloud-free data. However, imagery showing all three structures at one time are rare. The ones presented here are meant only as examples of these features. The dark portions of the picture represent warm temperatures, while the light portions represent cold temperatures. The extremely light portions are the cold tops of clouds. Newfoundland is the dark land mass in the upper left corner of each image. The line drawing on the bathymetry chart is a composite of all of the imagery for 1978 drawn by hand on a common grid. The solid line represents the edge of the cold water of the Labrador Front. The dashed line represents the direction and type of extrusion away from the front. The shaded area northwest of the front represents the dominant position of the Labrador Current as seen in the imagery. The smaller shaded areas in the west are smaller slope water current features that also appeared in the 1978 imagery. Composites drawn for other years' imagery show similar results.

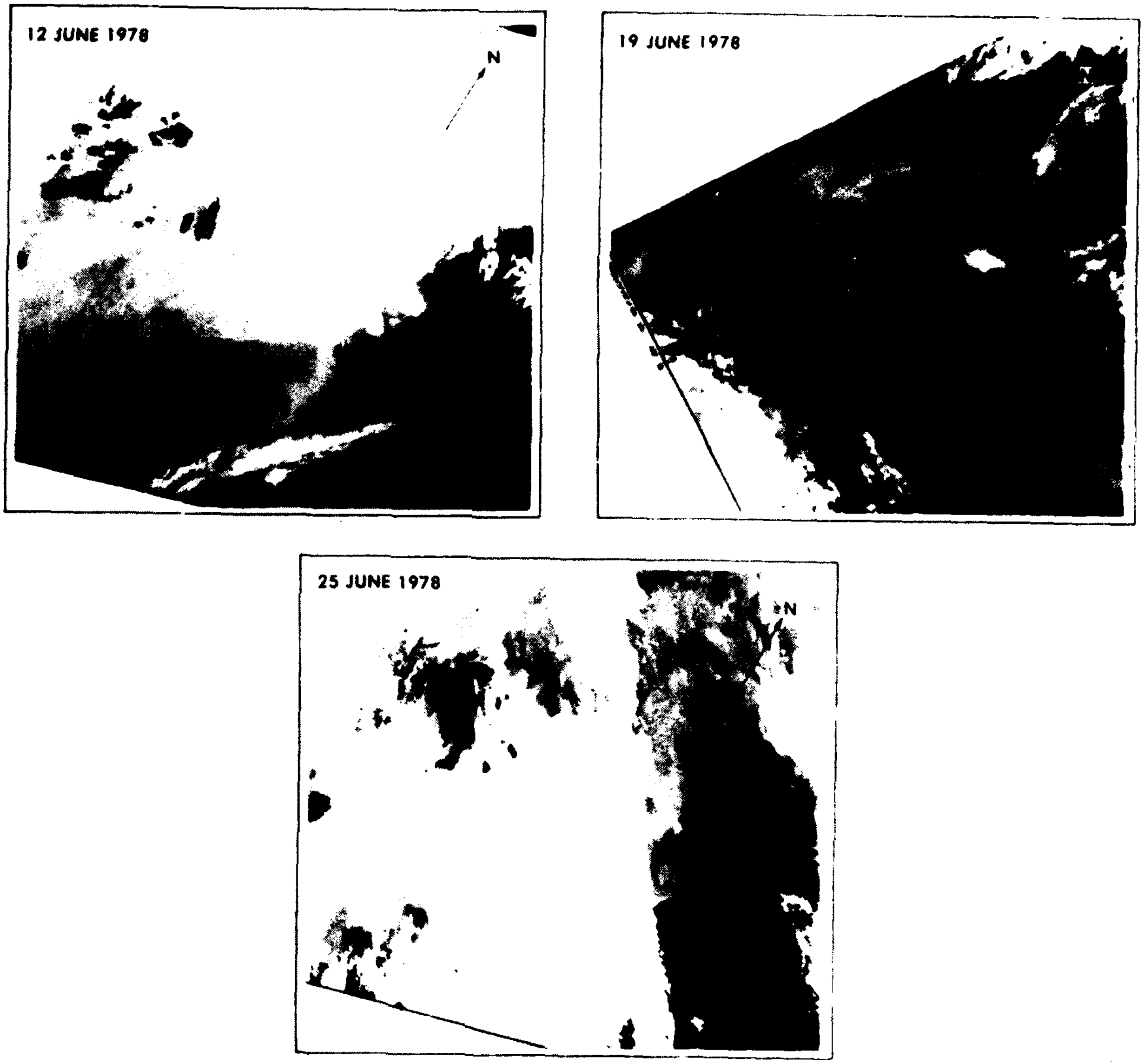


Figure 6. Selected NOAA-5 infrared imagery for varous days of the Baseline phase of the Grand Banks Experiment (June 1978). Although the figures have been enhanced to accentuate ocean thermal gradients, no attempt has been made to register the imagery into a single geographic grid. Because of distortion, the imagery for each day are not directly comparable to one another. As in the previous figure, Newfoundland is the dark mass in the upper left corner of each image. The frontal extrusion over the Southeast Newfoundland Ridge is shown in various stages of development in the lower right corner. Satellite imagery are available for the entire survey period. The imagery presented here is meant to show the best examples of the movement of the cold frontal water extrusion during Baseline.

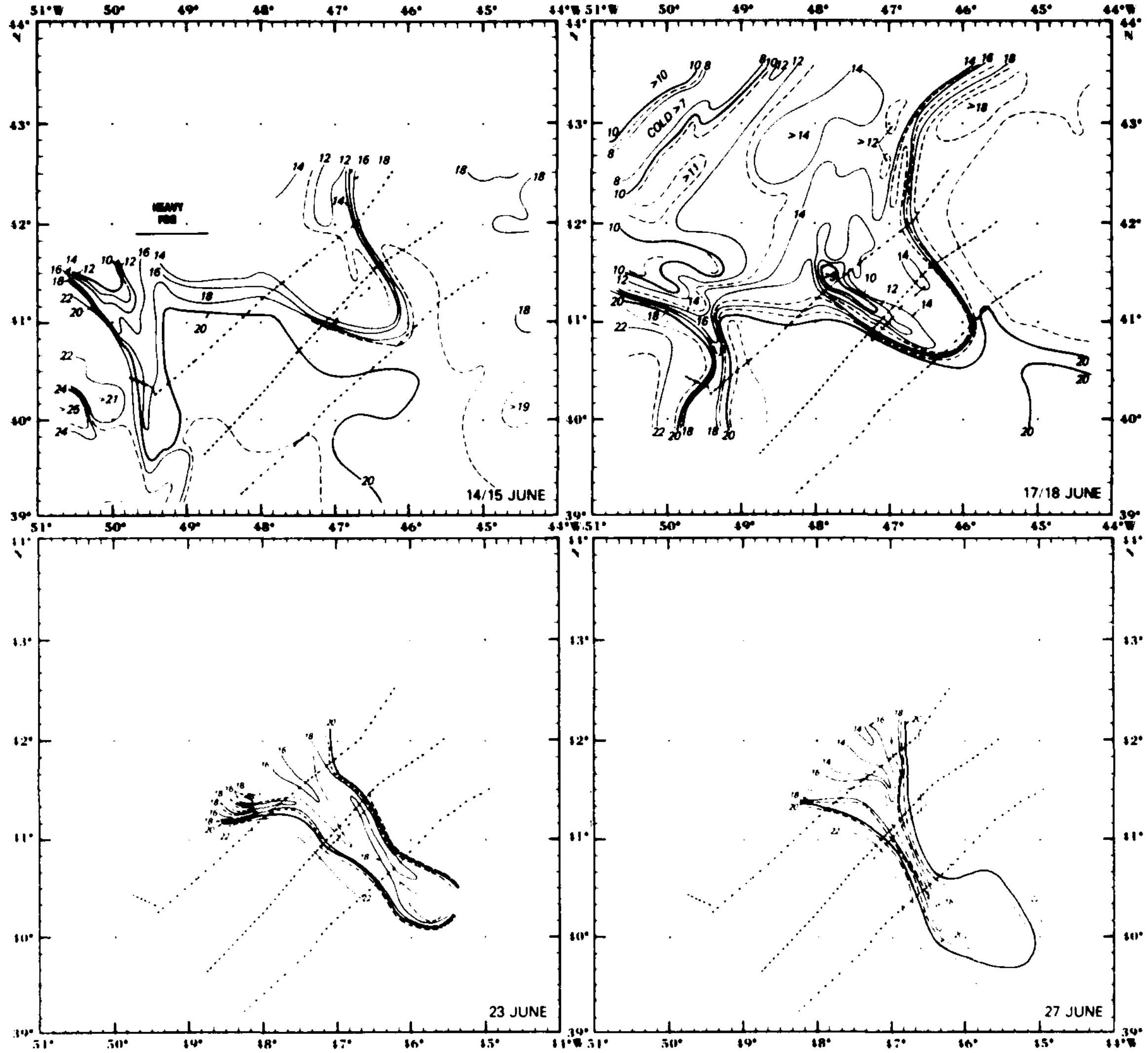


Figure 7. Analyses of aircraft Precision Radiation Temperature (PRT) data in ^{o}C for the ocean surface temperatures during Baseline. The four diagonal lines refer to drop location of ship and aircraft XBTs whose data are analyzed in Figures 11 and 14. In the 14/15 June analysis, the aircraft flew on the western side on 14 June and the eastern side on 15 June. In the 17/18 June analysis the aircraft flew the western side of the Figure on 18 June and the eastern side on 17 June. In flying the western and eastern flight tracks, a 50 km overlap was maintained.

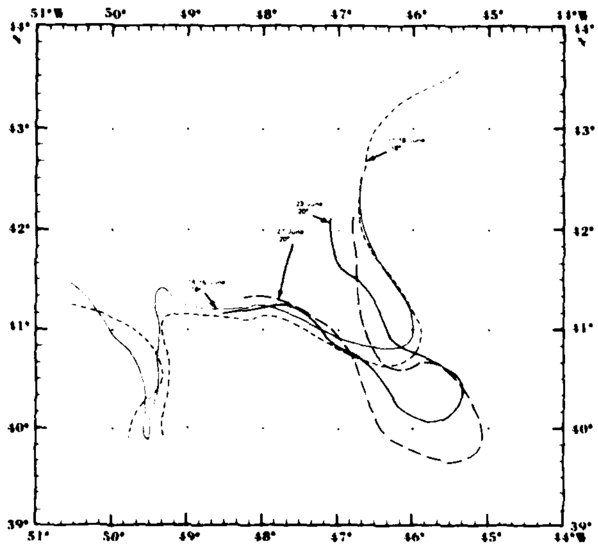


Figure 8. Progression of the extruding cold frontal feature over the Southeast Newfoundland Ridge between 14 and 17 June 1978. Each isoline represents the position of the main thermal gradient for the representative day's flight.

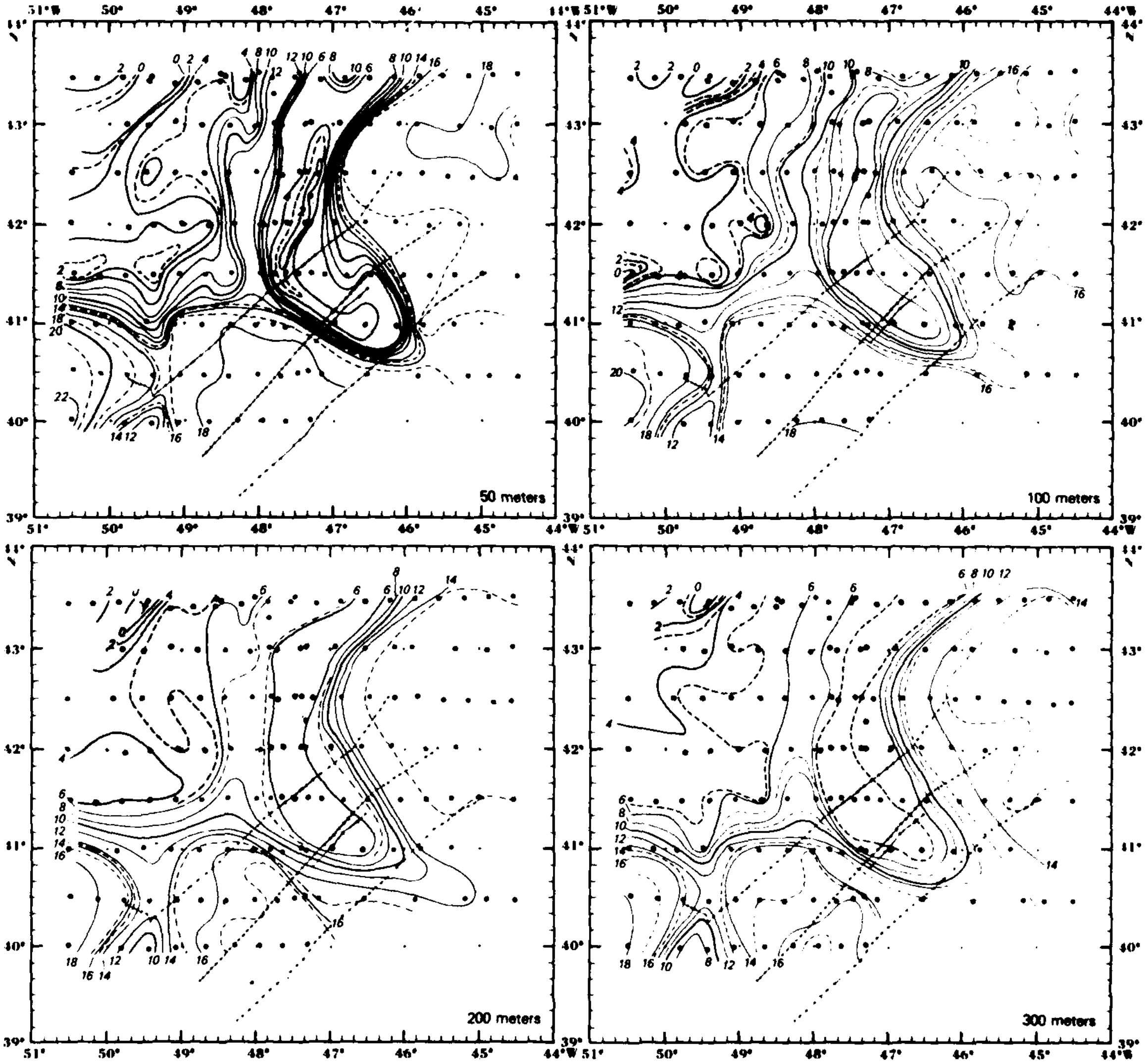


Figure 9. Horizontal analyses in $^{\circ}C$ of aircraft 350 m XBT data obtained on 17/18 June. The solid dots refer to the drop locations of the XBTs. The four diagonal lines refer to the drop location of ship and aircraft XBTs whose data are analyzed in the cross-sections in Figures 11 and 14.

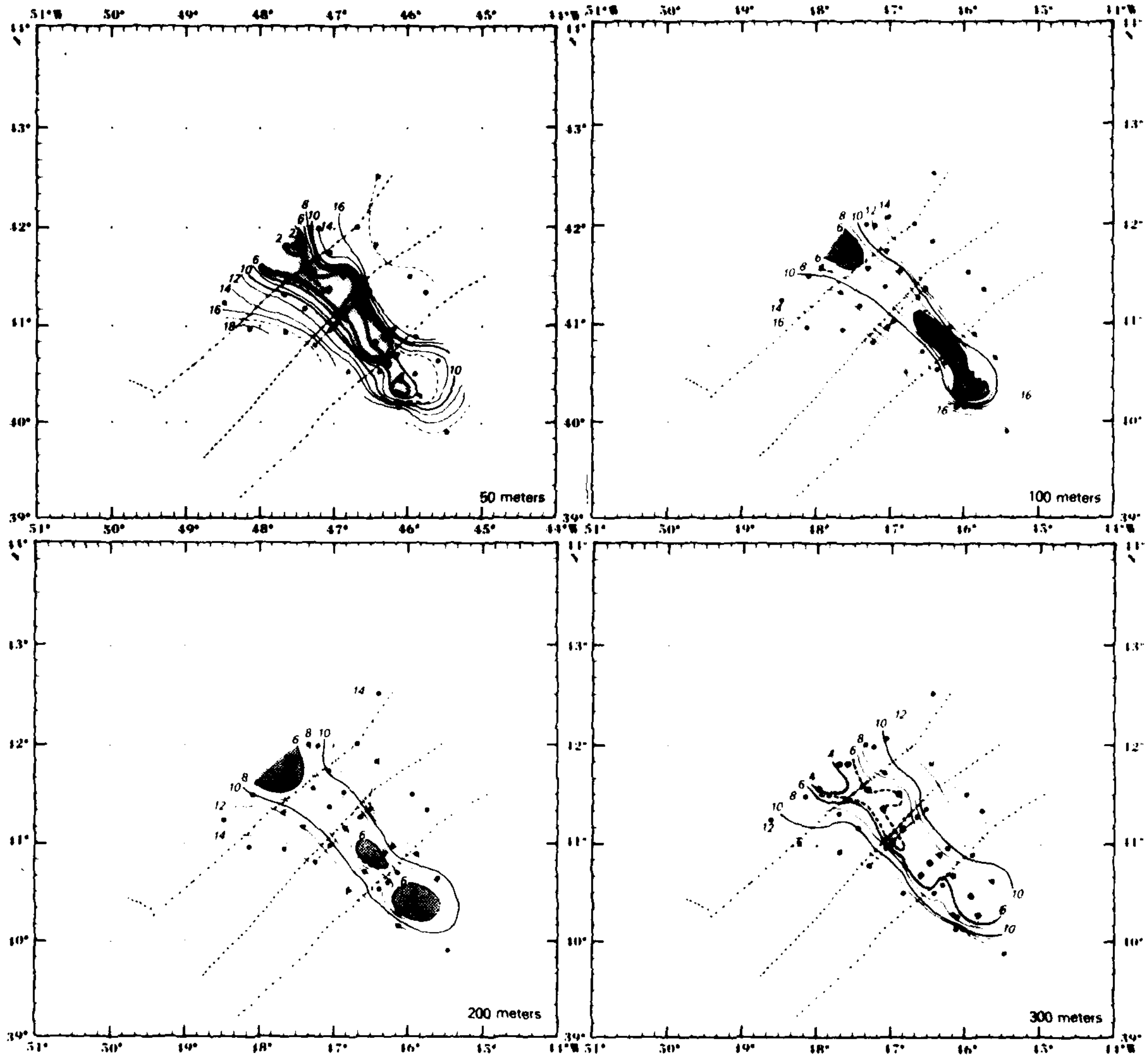


Figure 10. Horizontal analyses in ^{o}C of aircraft 350 m XBT data obtained on 23 June 1978. The solid dots refer to the drop locations of the XBTs. The short diagonal line in the center of the feature refers to the location of the XBT cross section for the same day shown in Figure 13. The other three longer diagonal lines refer to the drop location of the ship XBTs whose data are analyzed in the cross sections in Figure 14.

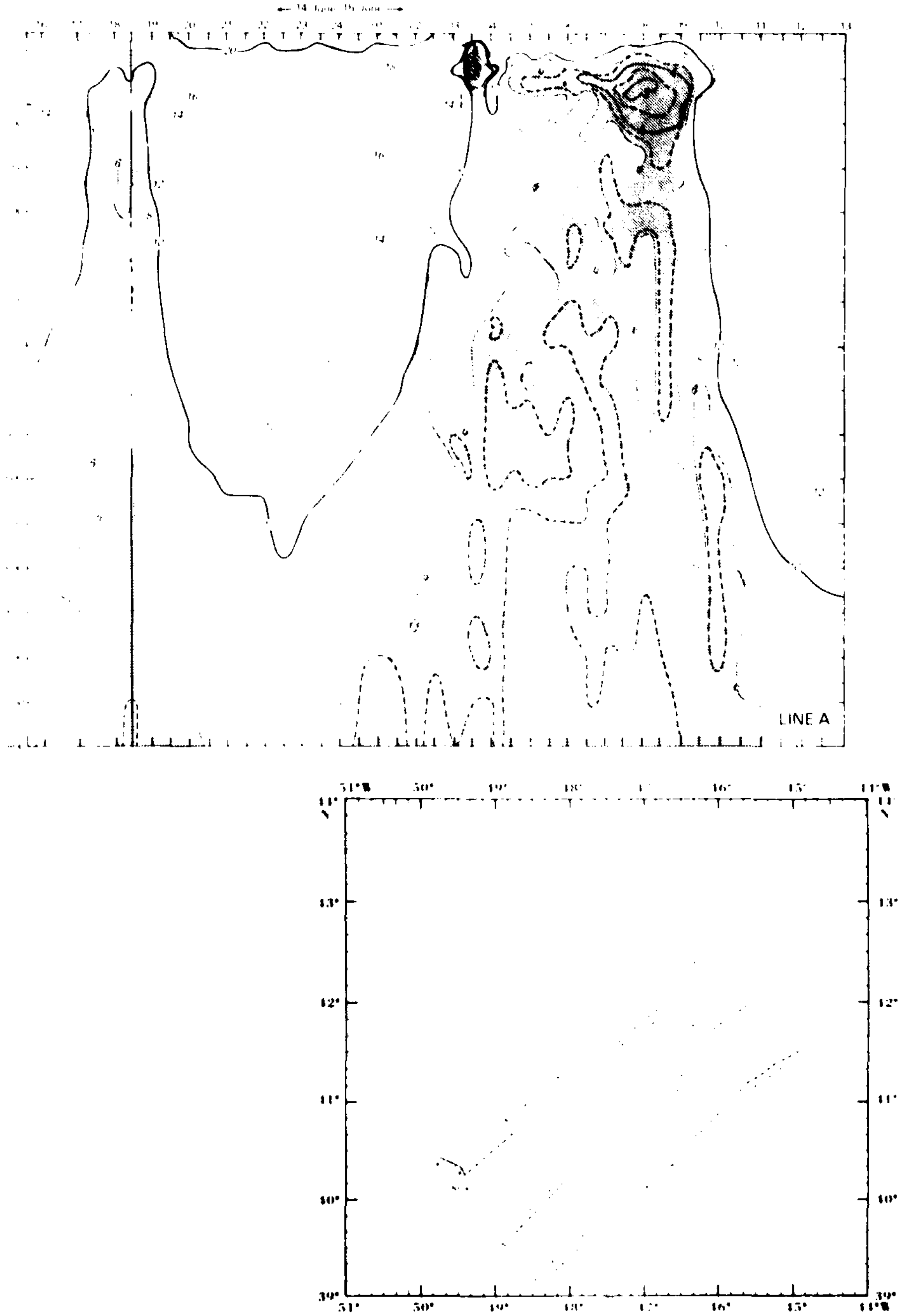
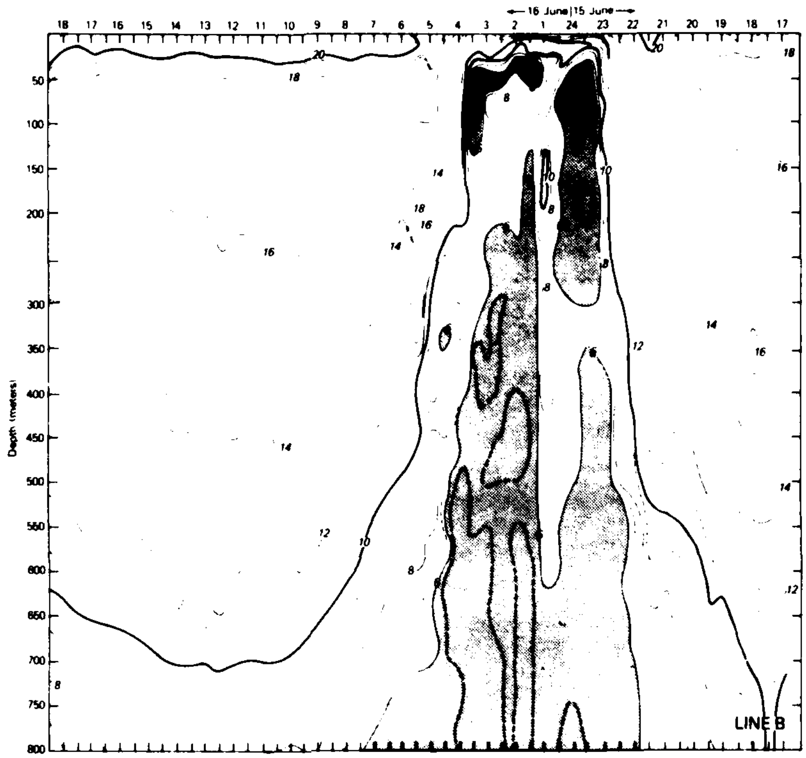


Figure 11. Vertical analyses in ^{o}C of ship 750 m XBT data during Baseline. The XBTs were dropped every 1/2 hour and the values at the top refer to the Greenwich Mean Time (GMT) as well as the drop location of each XBT. The vertical line at 1830 GMT, 14 June of Line A refers to the change in direction shown in the locator chart. The XBT data from 1030 to 1130 GMT, 17 June, of Line C were considered unreliable. Note that double-minimum temperatures are visible in the cold features of all three vertical sections with the core of the first minimum temperature situated between 50 and 100 m. The position of the core is better shown in the horizontal display in Figure 15. Data from the line of XBTs marked "23 June" in the locator chart are analyzed in cross-section in Figure 13.



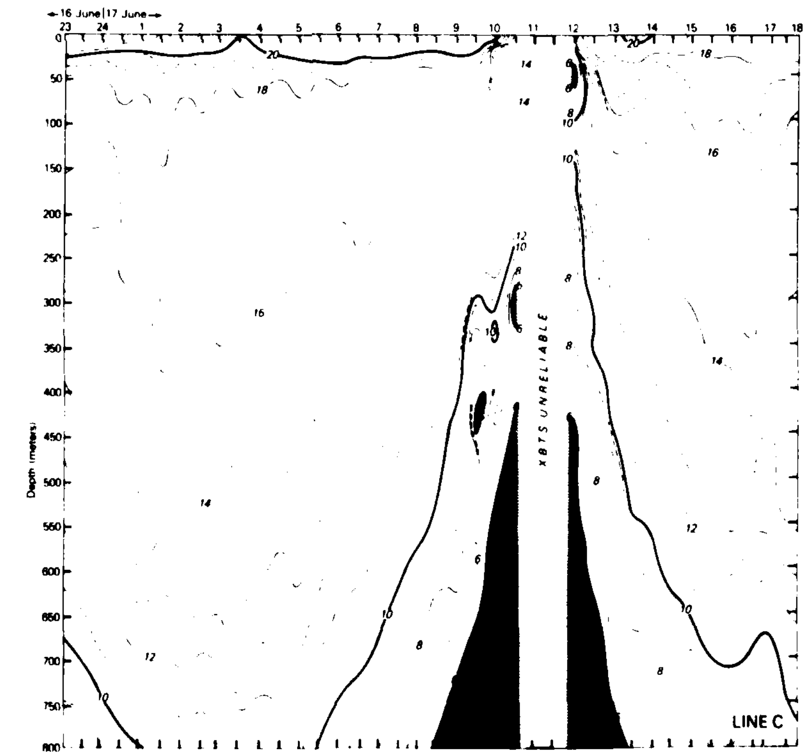


Figure 11. (cont.)

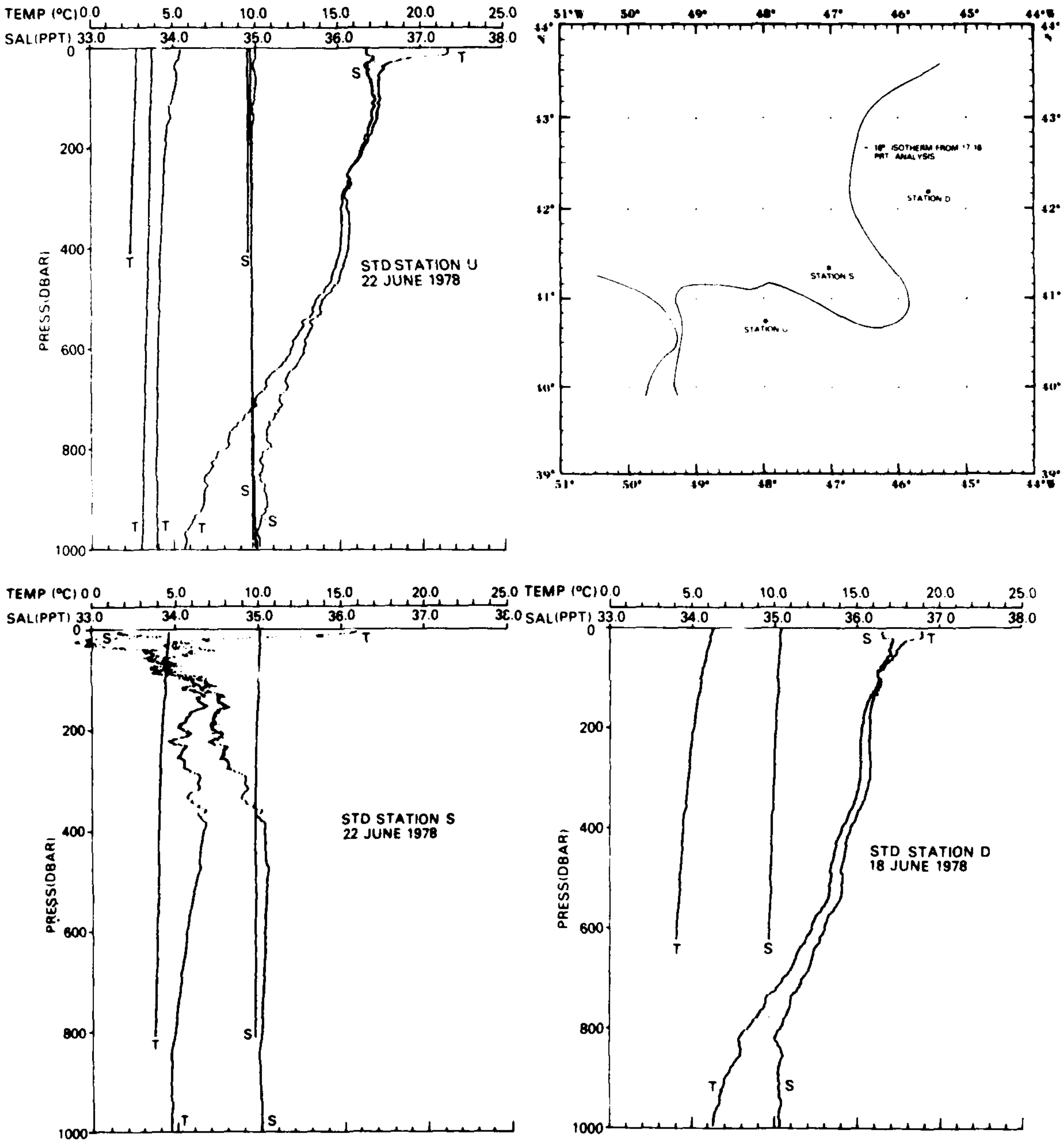


Figure 12. Representative STD stations across the cold frontal feature lying over the Newfoundland Ridge during Baseline. Although 26 STD stations were made, the rapid movement of the front prevented subsurface areal analyses.

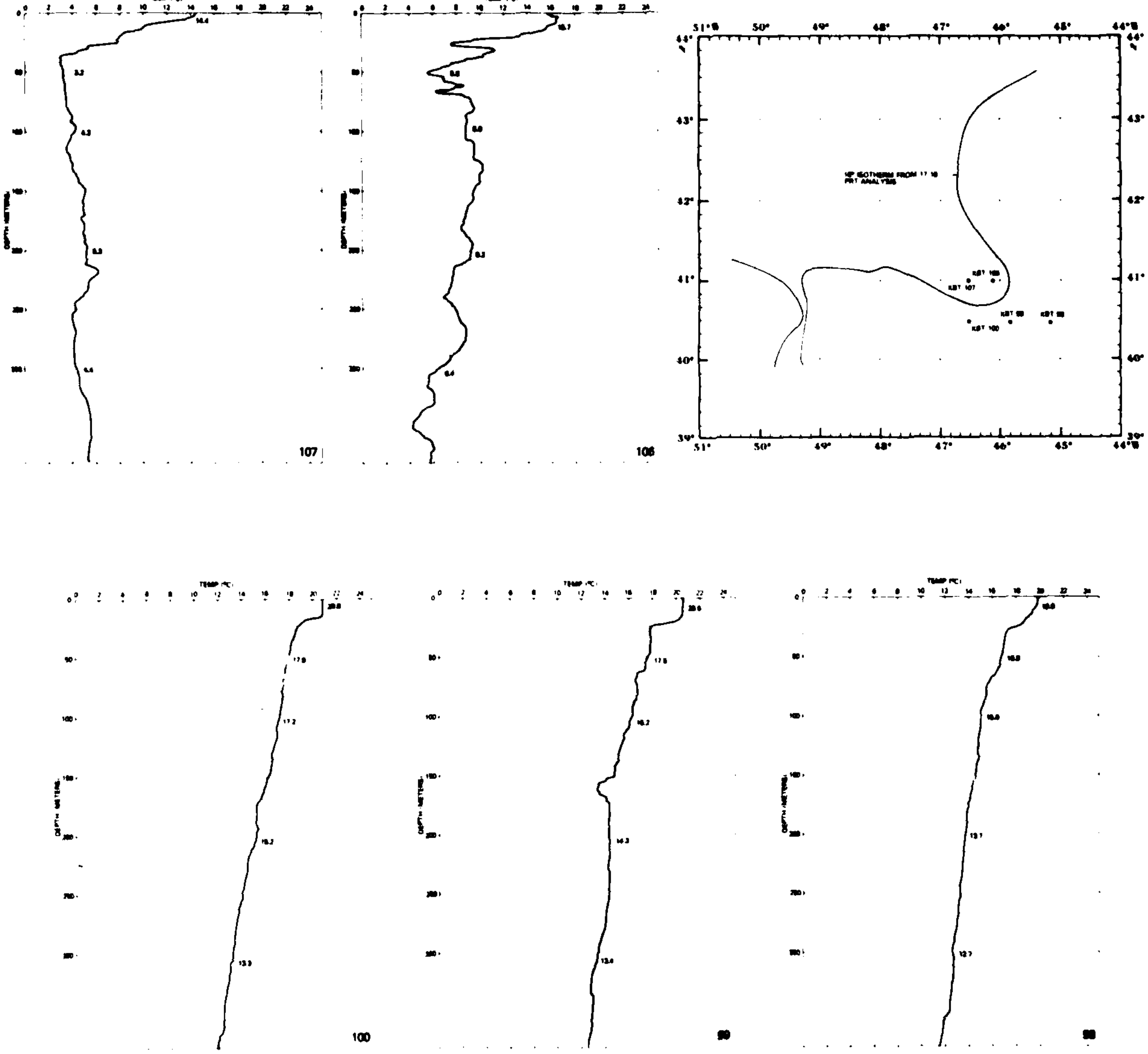


Figure 13. Vertical temperature traces for aircraft 350 m XBT's dropped on 17 June 1978 behind and just ahead of the advancing Newfoundland Ridge frontal feature.

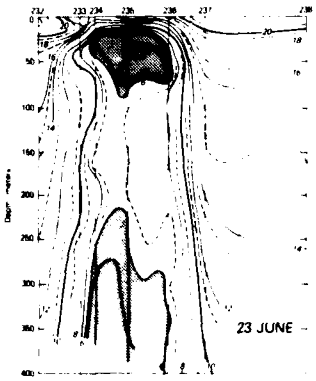


Figure 14. Vertical analysis in ^{o}C of data from aircraft XBTs throughout 23 June 1978. The double minimum shown in the ship XBT cross-sections of 14 though 17 June in Figure 11 is still present. The core of the first minimum (<3^{o}C water) is visible at slightly less than 50 m.

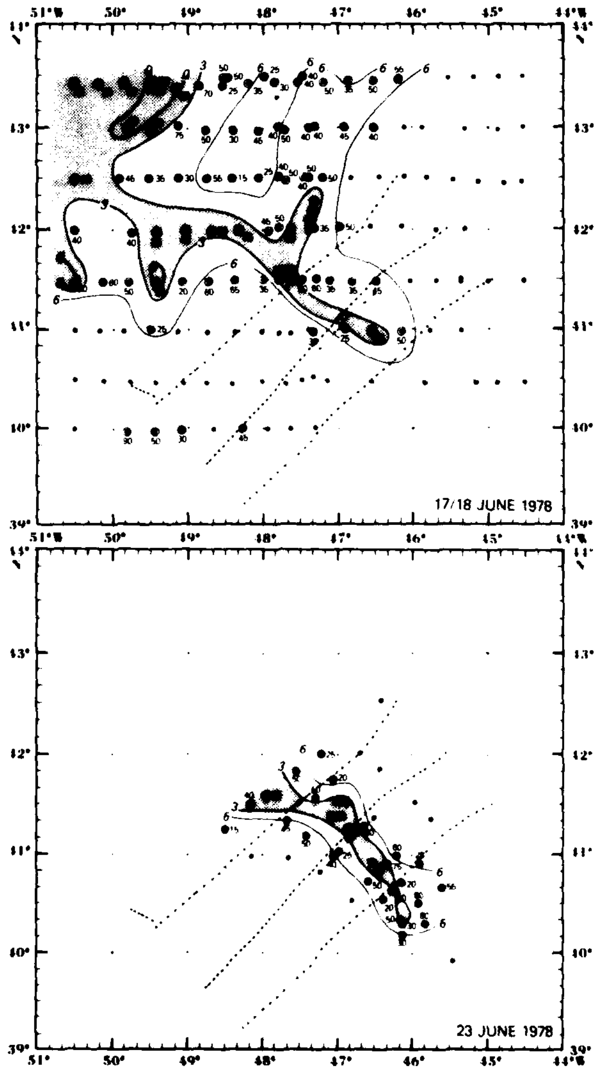


Figure 15. The position of the first minimum temperature for 17/18 and 23 June 1978. The position of aircraft XBTs whose data showed double minimums is shown by the circled solid dots. The values immediately below the dots are the depth in meters of the core of the first minimum. The isolines refer to the value in °C of the core. The four diagonal lines refer to the drop locations of ship and aircraft XBTs whose data are analyzed in the cross sections in Figures 11 and 14.

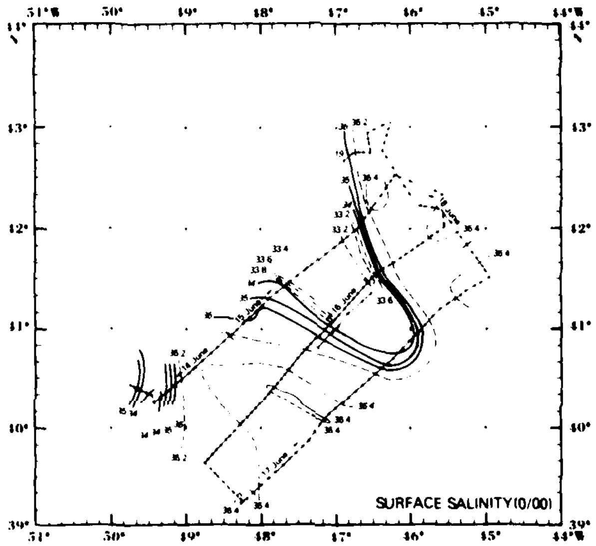


Figure 16. Analysis of surface salinity data collected by the USNS LYNCH from 14 through 18 June 1978.

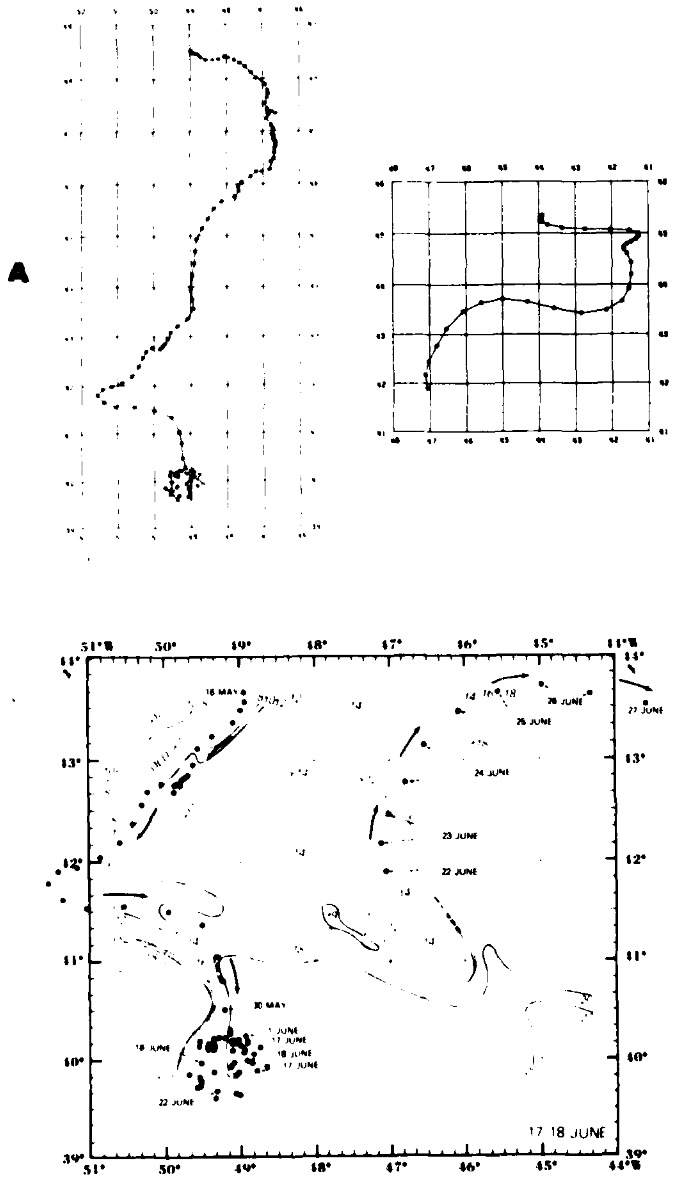


Figure 17. Movement of satellite drifter buoys within the Grand Banks Experiement area during Baseline (Richardson, 1980). The drifter buoy in (a) was released by the USCGC EVERGREEN on 13 April; the buoy in (b) was released by the USNS LYNCH on 22 June. The dots represent positions at time intervals of approximately twice a day (1200 and 2400 GMT). The 17/18 June PRT analysis is presented to give perspective to the position of the thermal gradients during a portion of the buoy's movement. The entire track of the western buoy in (a) may be further compared to the position of the Labrador Current shown as the cold north-south sinuous feature in the lower section of the 12 June satellite image in Figure 6. The entire track of the eastern buoy may be compared to the position of the northern of the two extrusions in the 25 June image of Figure 6.

Figure 18. TIROS-N infrared image for 15 May 1979 showing extrusions over the southeast Newfoundland Ridge and the Newfoundland Seamounts. TIROS-N data, unlike NOAA-4 and 5 data, can be made into accurate registered imagery. The original distorted image is presented at the top of the figure (the arrows designating the north wall of the Gulf Stream). The bottom two images have been registered into a mercator grid and digitally enhanced to show various oceanographic features. The dark filament in the enhancement on the right shows a branch of the Gulf Stream going around the Newfoundland Ridge feature.

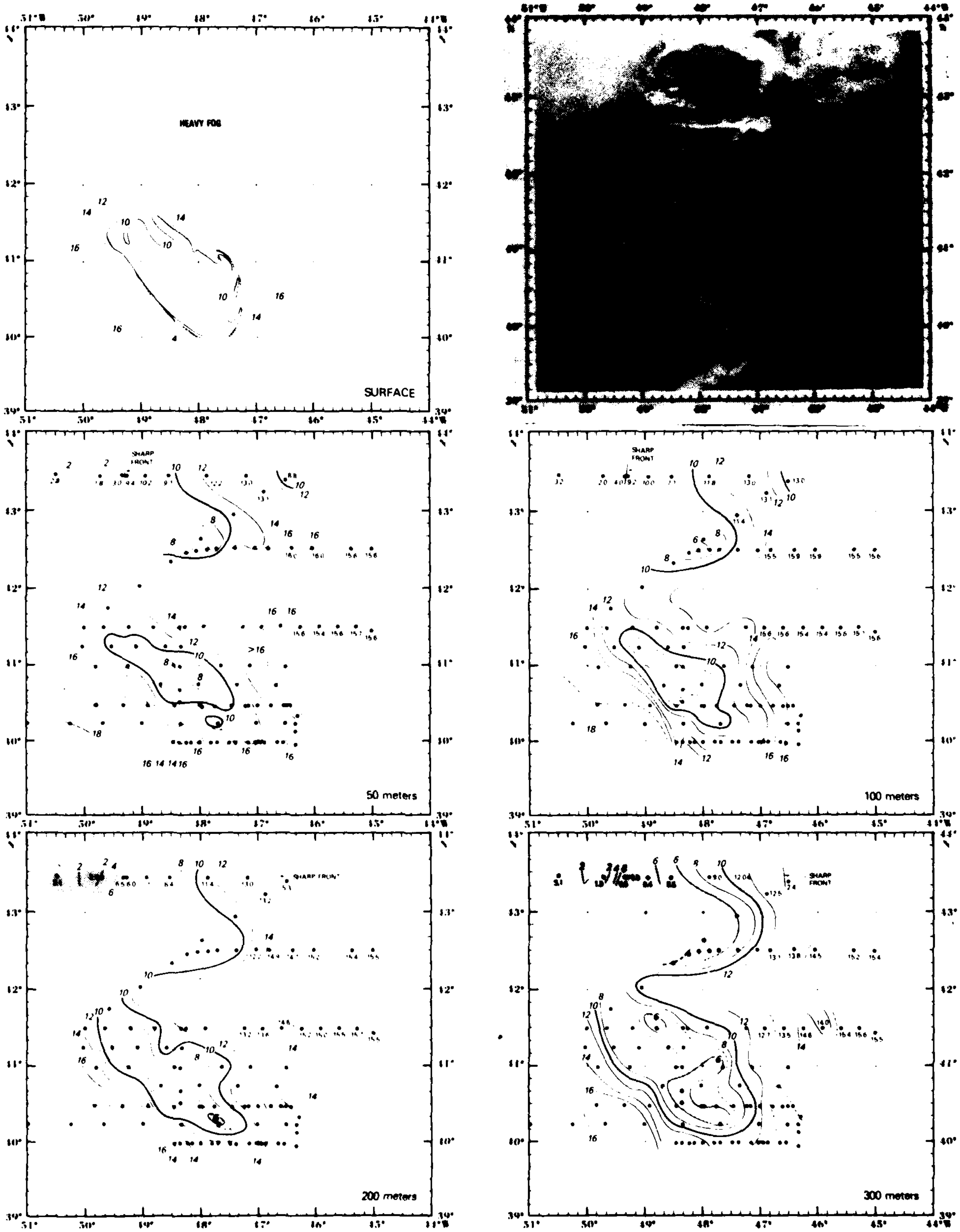


Figure 19. Horizontal analyses in ^{0}C of 9/10 May aircraft PRT data (surface) and 350 m XBT data (50 to 300 m). The analysis for the surface has been superimposed on the TIROS-N 15 May image to show the small amount of movement that had taken place in the five days.

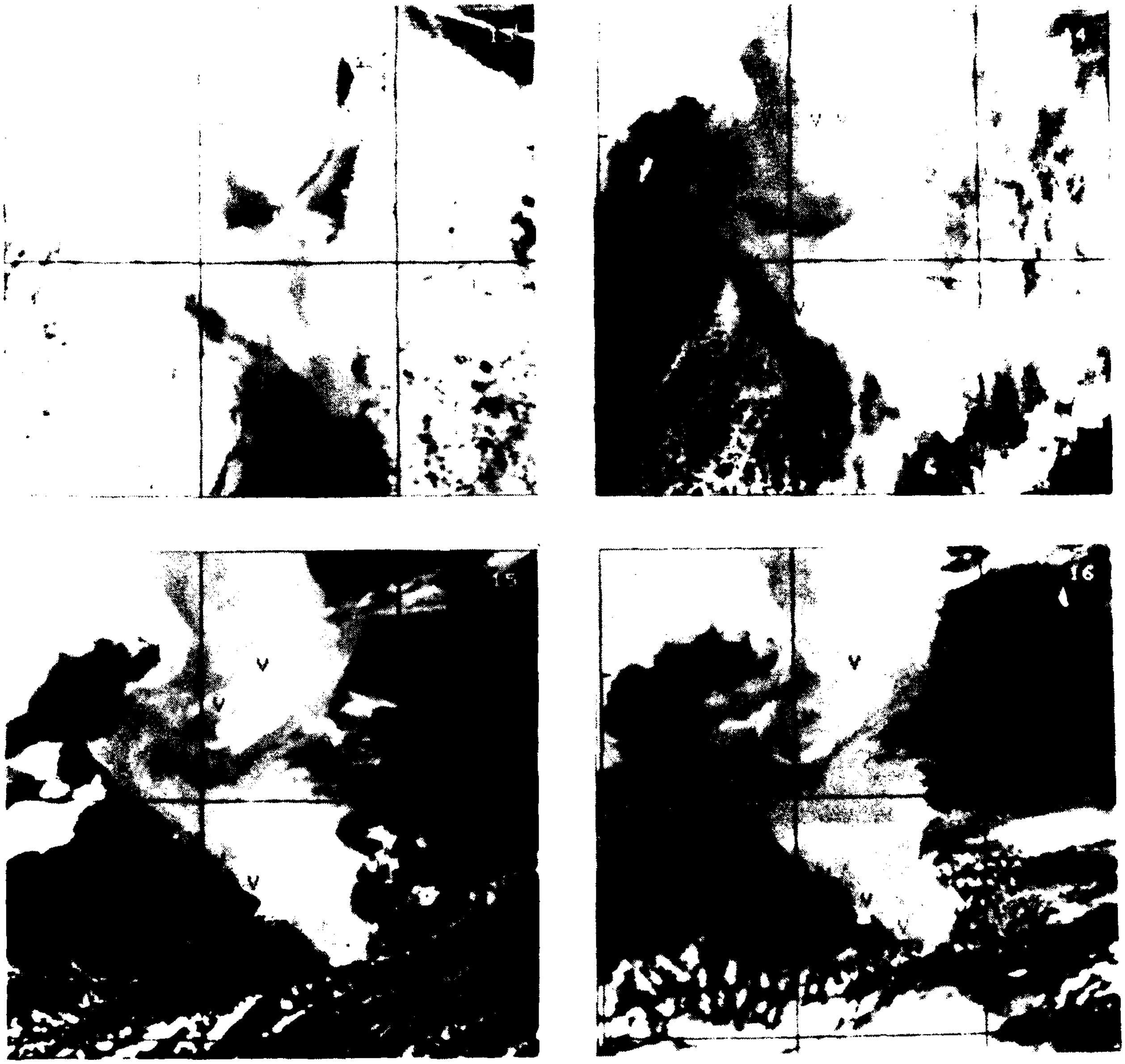
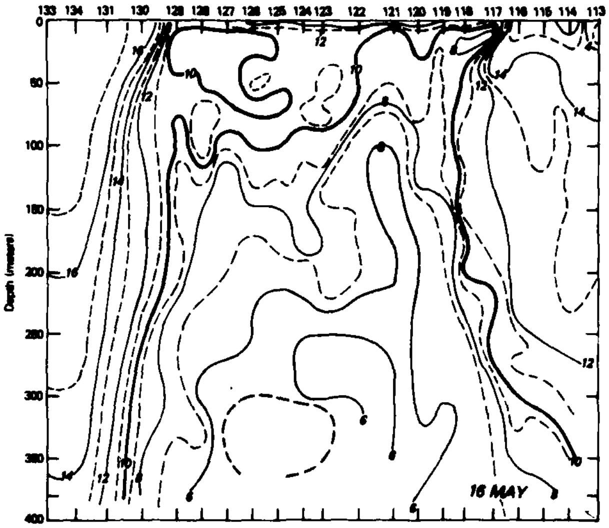
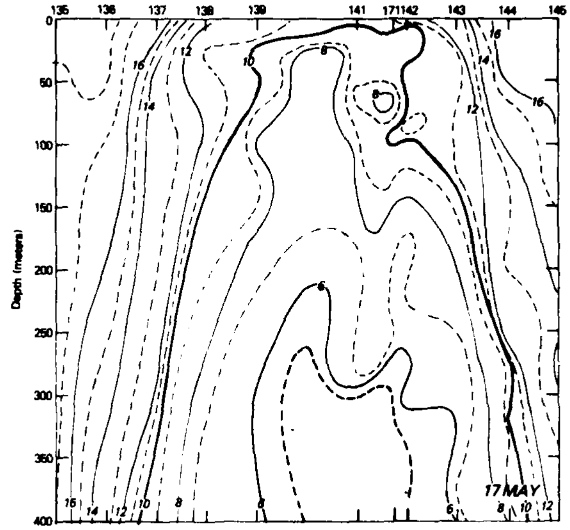


Figure 20. TIROS-N satellite imagery for 13, 14, 15 and 16 May 1979 showing the day-to-day movement of the Southeast Newfoundland Ridge frontal feature. The latitudinal and longitudinal lines form 2° squares. Their values may be derived from the 15 May TIROS-N image in Figure 19. The arrows point to identifiable portions of the feature that moved during the four-day period.





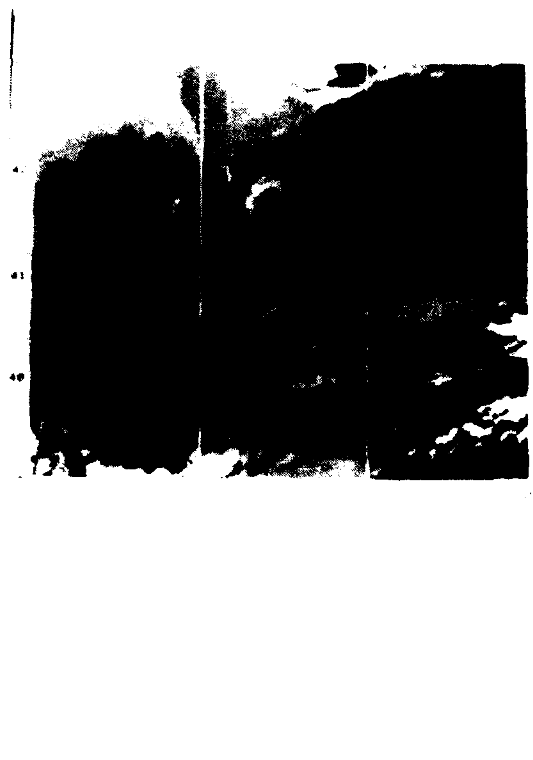


Figure 21. Vertical analysis in ^{o}C of data from aircraft XBTs dropped on 16 and 17 June 1979. The tracks of the aircraft during the drops are shown on the 16 May 1979 TIROS-N image.

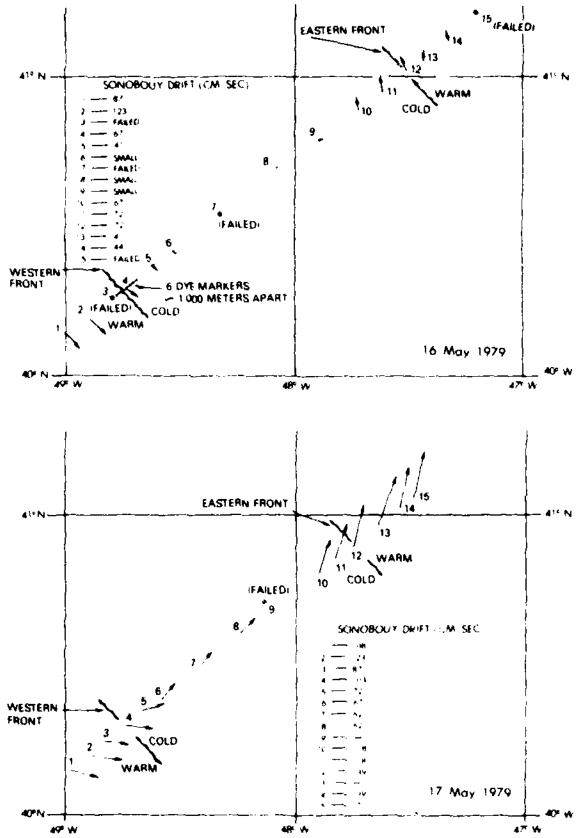


Figure 22. The initial and end positions of the 38 sonobuoys dropped on 16 and 17 May. The tracks for the drop position were the same on both days and correspond to the 16 May XBT track of Figure 21. The drop positions of the dye markers are shown between positions 2 and 5 of 16 May.

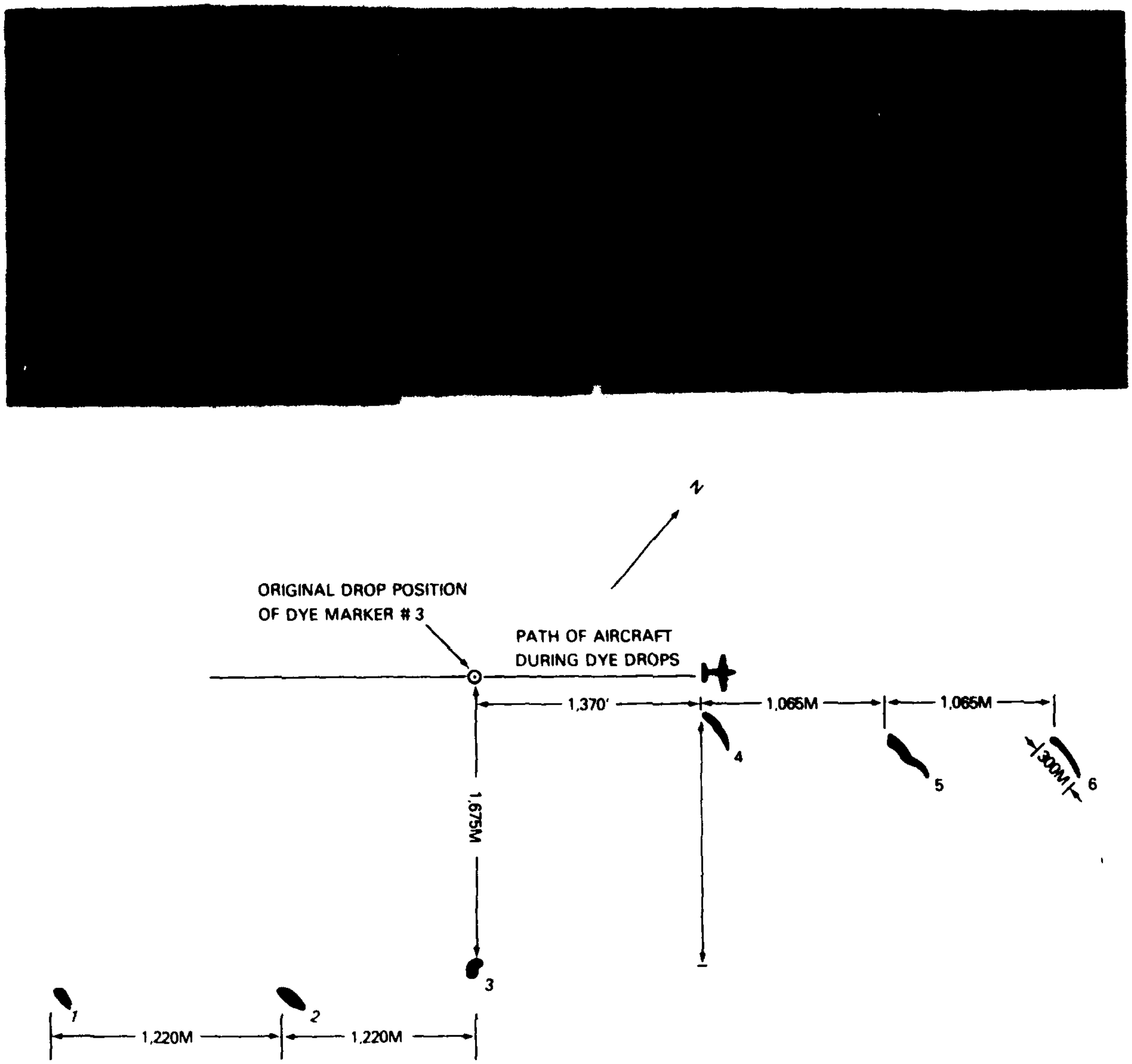


Figure 23. A photographic mosaic of the drift positions of the dye markers dropped on 16 May. The time between the dropping of the dyes and the photographs was one hour and ten minutes.

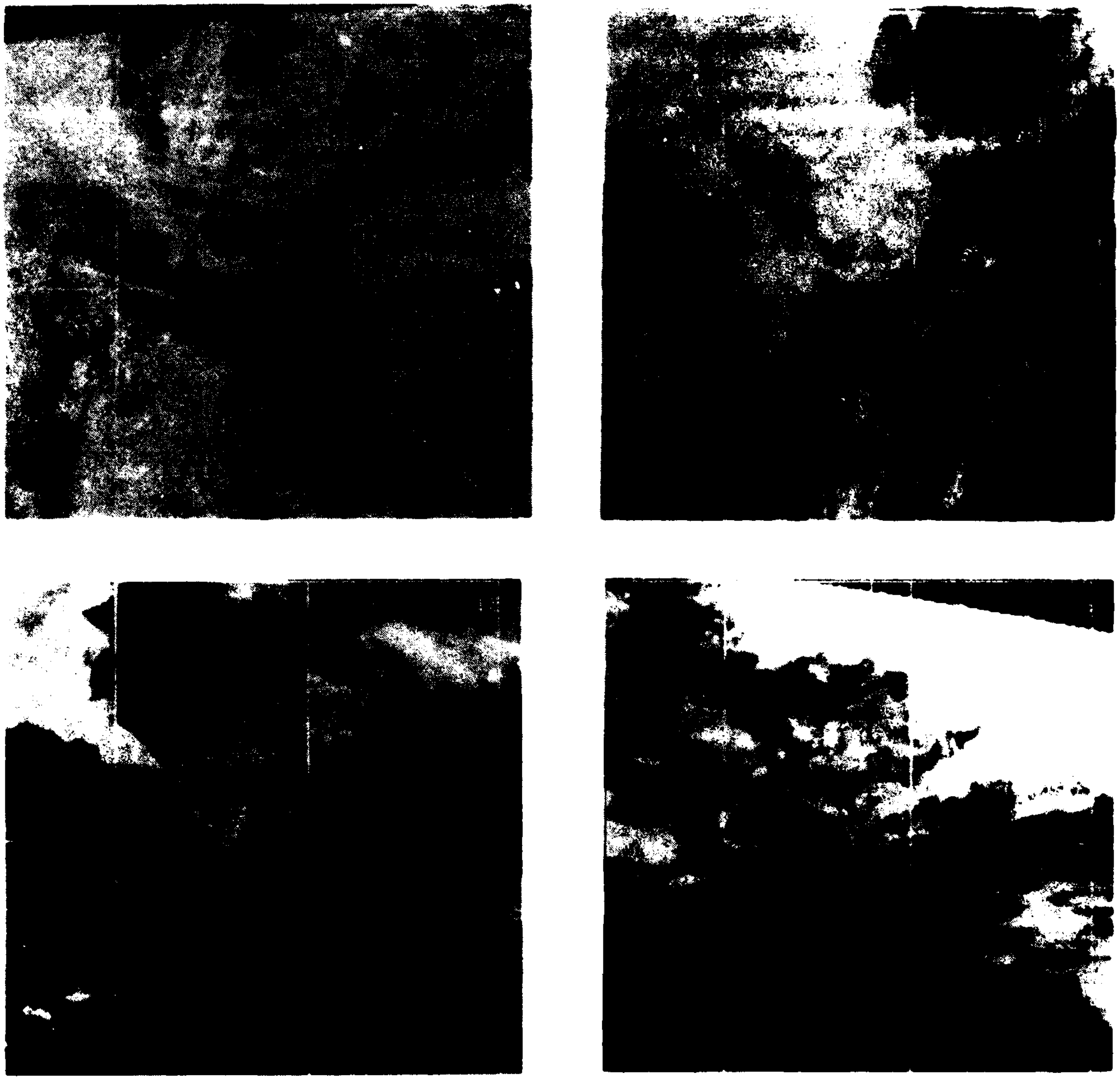


Figure 24. TIROS-N satellite imagery for 13, 14, 15 and 16 May 1979 showing the day-to-day movement of the Newfoundland Seamounts' frontal feature. The latitudinal and longitudinal lines for 2^{o} squares. Their values may be derived from the 15 May TIROS-N image in Figure 19. The arrows point to an identifiable portion of the feature that moved during the four-day period.

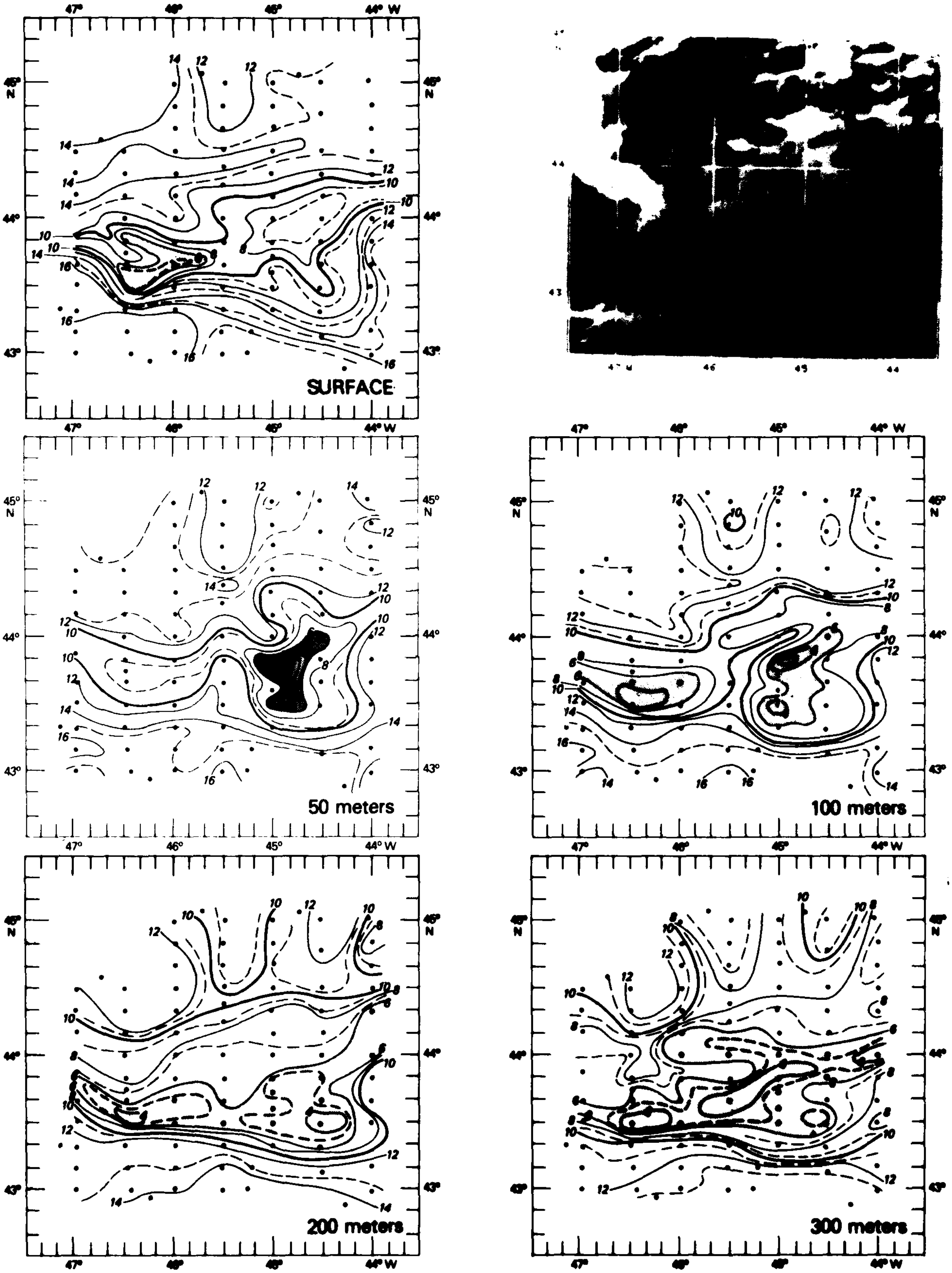


Figure 25. Horizontal analysis in ^{o}C of 19 May 1979 aircraft XBT data. The dots represent the drop locations of the XBTs. TIROS-N imagery for 16 May is presented to show the details of surface structure not presented by the XBT surface analysis.

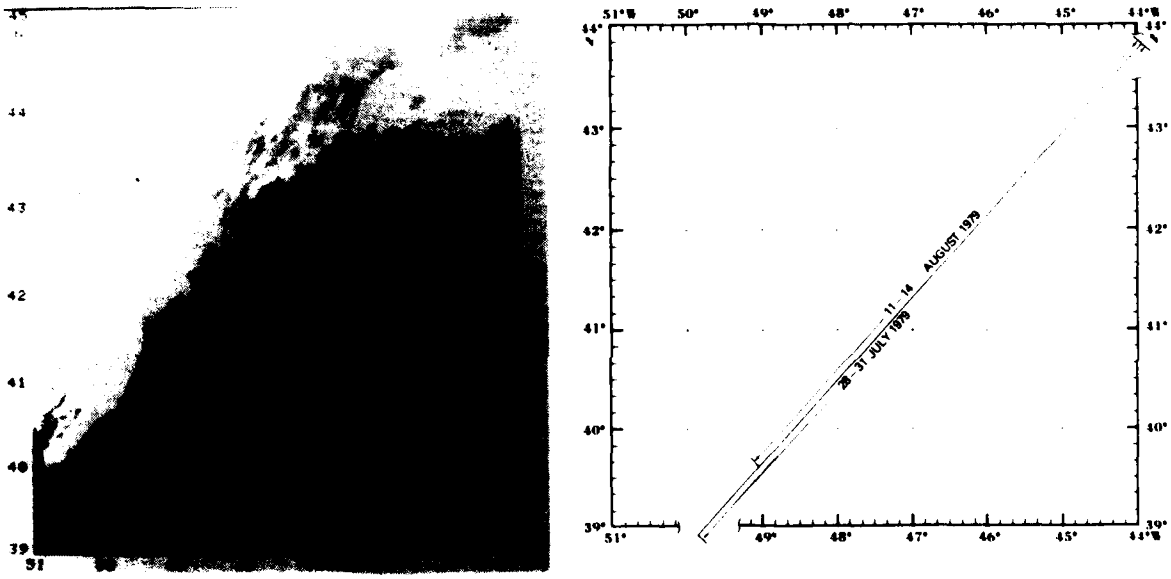


Figure 26. TIROS-N image for 28 July 1979 showing the track of USNS LYNCH for the period 28 through 31 July. The adjacent chart shows the double tracks of the ship in July and August.

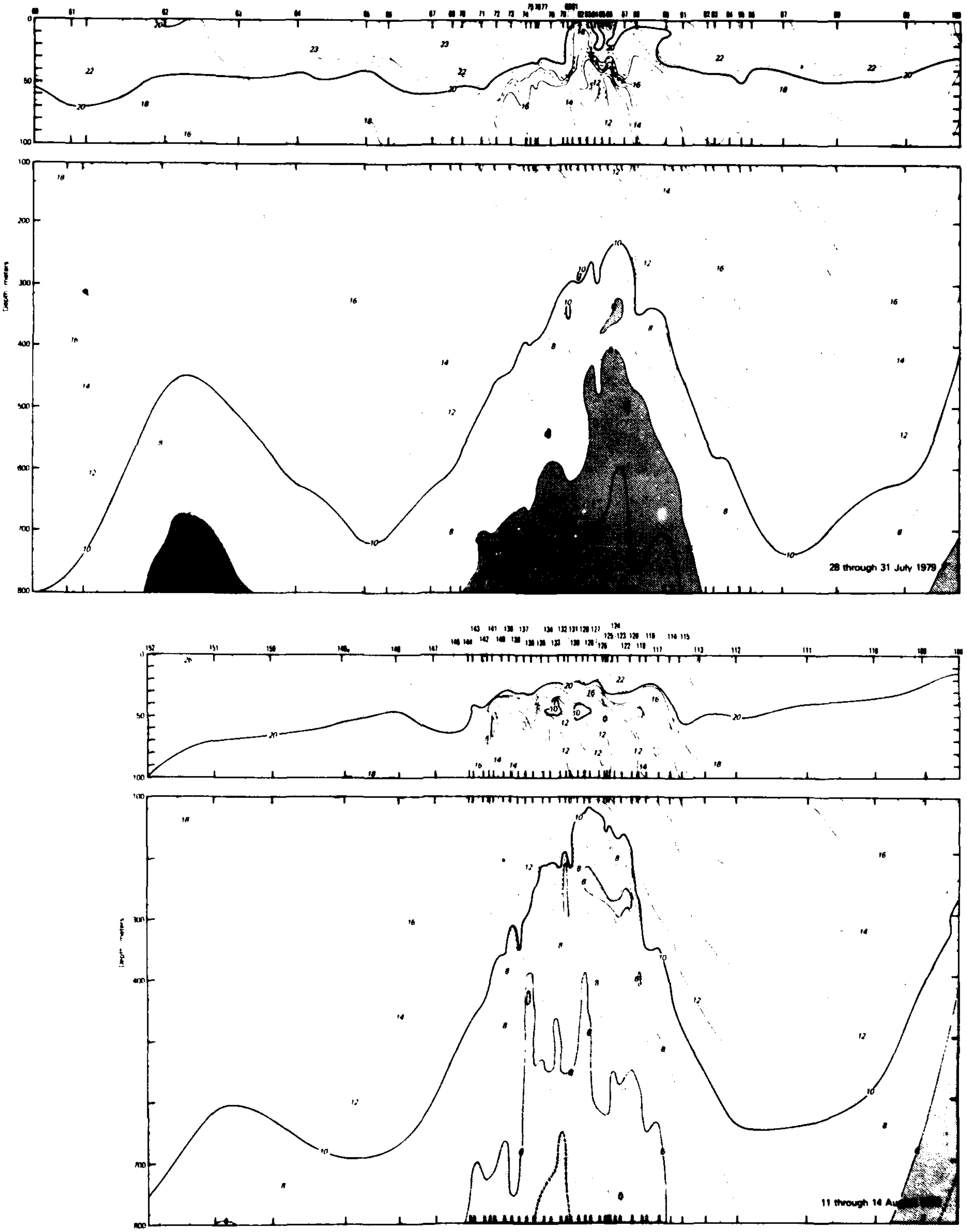


Figure 27. Vertical analysis in ^{o}C of ship 750 m XBT data dropped in July and August 1979. See Figure 26 for location chart. The depth scale for the first 100 m has been expanded to show the details of this depth interval.

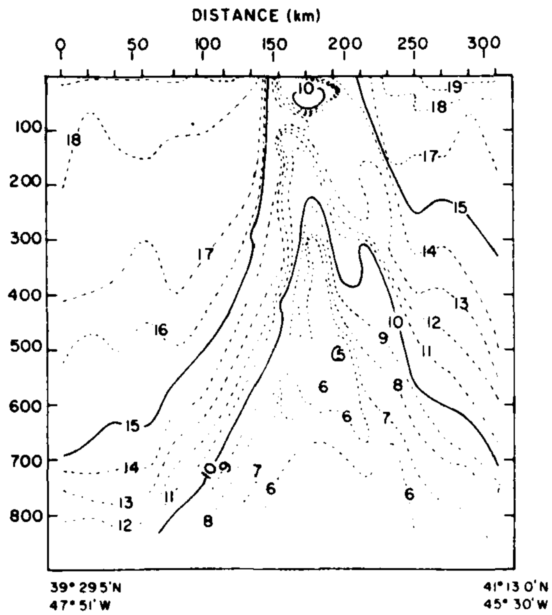


Figure 28. Vertical analysis on ^{0}C of R/V HUDSON XBT data for 18 May 1972 after Reininger and Clarke (1975). This section was made close to Line C of Figure 11 and lies along Line A/B of Figure 29.

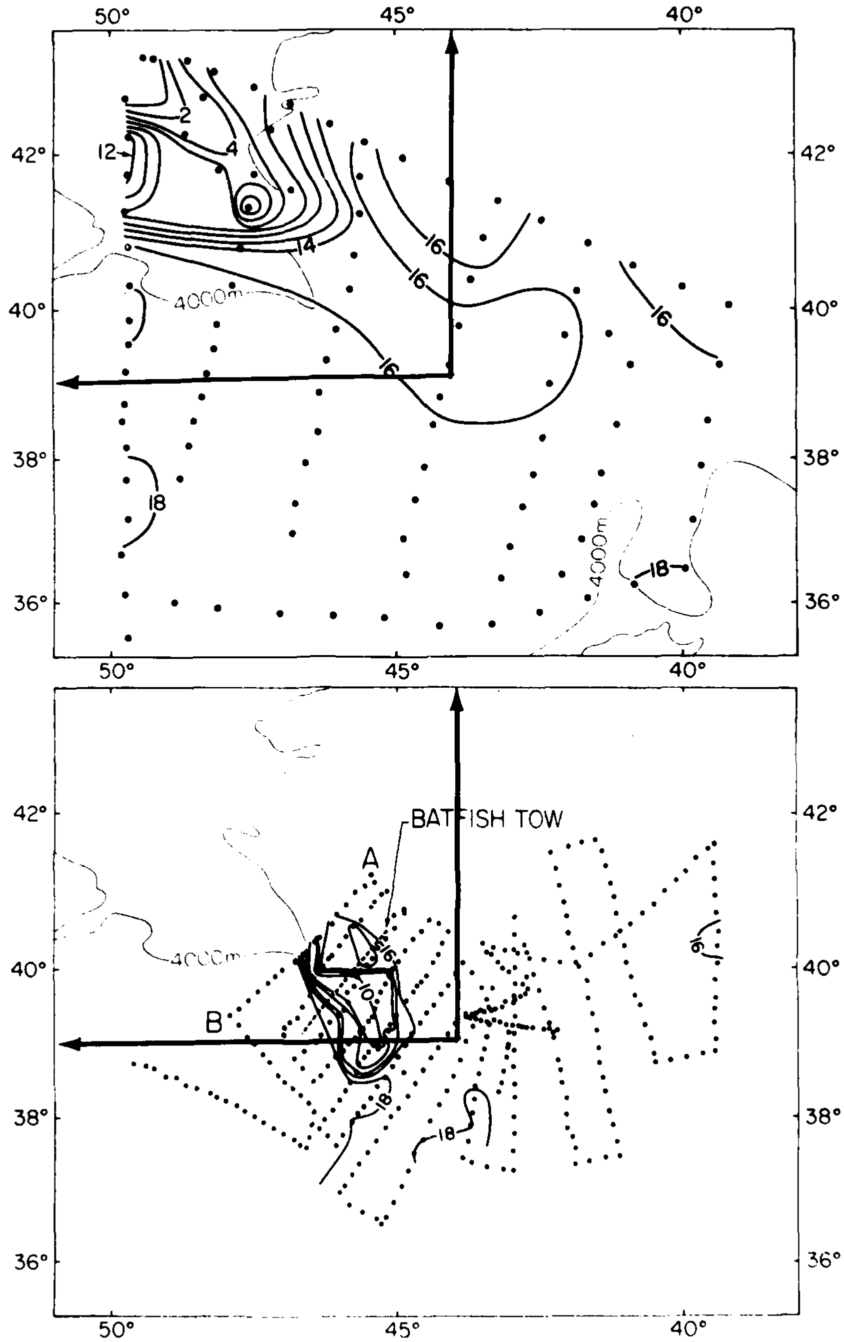


Figure 29. Horizontal movement of the 10°C isotherm at 50 m during the three-ship survey in 1972 (after Reininger and Clark, 1975). The upper figure shows an analysis of data from hydrographic casts collected by R/V HUDSON and R/V CHAIN from 6 April to 9 May 1972. The lower figure shows analysis of XBT data collected by R/V HUDSON in the interval 18 May to 1 June 1972. The boxed area in the upper left of each figure refers to that portion of the figure in the present study. The line A/B is the location of the XBTs whose data were used in the vertical section in Figure 28.

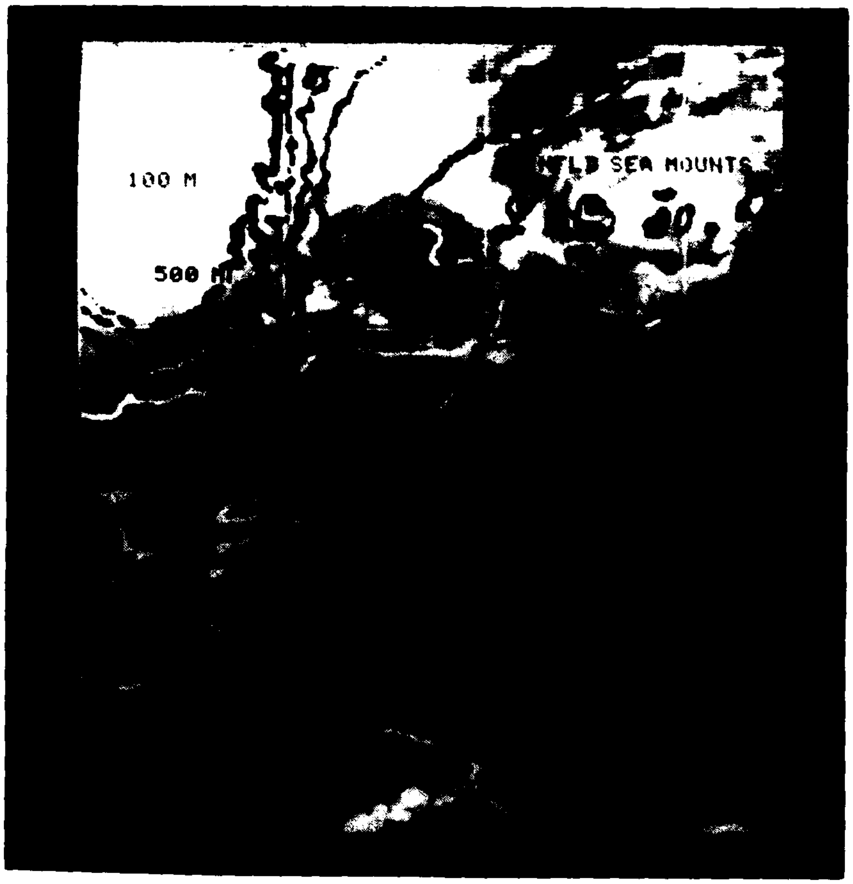


Figure 30. Superposition of the regional bathymetry adapted from Figure 4 onto the 15 May TIROS-N image.

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An examination of aircraft and ship data taken as part of the Grand Banks Experiment during 1978 and 1979, and satellite data collected for the period January 1975 through October 1979 shows that the complex changing patterns of thermal gradients in the waters off the southeastern Grand Banks are different phases of large, cold-water extrusions moving away from the Labrador Front. These, cold extrusions, well delineated by their strong surface temperature gradients in the spaceborne and airborne thermal radiometry data, are found to

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extend as deep as 1500 meters in the shpborne salinity and temperature data. Four of the frontal extrusions are studied in detail. Three of these are found to be always in some phase of extension, with the actual speed of extension varying considerably. Moreover. the three features are found to be always in some phase of extension. with the actual speed of extension varying considerably. Moreover, the three features are found to consistently overlay specific bathymetric rises: the Newfoundland Ridge. the Newfoundland Seamounts and the Flemish Cap. The fourth cold-water extrusion, which extended south along 49°30' W in some of the data, did not appear to be topographically influenced.

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